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Monterey, California

THESIS

Unsteady Effects on the
Measurement of Total
Pressure in Rotating Machines

by

Vernon James Larson

September 1977

Thesis Advisor: R.P.Shreeve

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20. ABSTRACT (Continued)

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It was concluded that the corrections required to be
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Unsteady Effects on the
Measurement of Total
Pressure in Rotating Machines

by

Vernon James Larson
Lieutenant, United States Navy
B.S., Oregon State University, 1968

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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Author _____

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Thesis Advisor

_____
Chairman, Department of Aeronautics

_____
Dean of Science and Engineering

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ABSTRACT

The pressure averaging of different pneumatic impact probes was investigated using a periodic flow generator in order to establish corrections for probe measurements made in a compressor, and to guide the selection of probe geometries to be used in the compressor. The Kulite transducer probe used as a reference in these measurements was also used, with both continuous and synchronized sampling, to measure the flow from the compressor rotor. It was concluded that the corrections required to be made to the pneumatic impact pressure measurements were negligible at 50% design speed, but might be significant at higher speeds if the probe system volume were not properly sized.

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I. INTRODUCTION

The work reported here is part of an on-going effort at The Naval Postgraduate School to determine the aerodynamic characteristics and performance of the blading of a single stage, axial transonic compressor using real-time instrumentation. The performance is to be compared with the results of measurements made using conventional pneumatic instruments.

In work already reported, compressor case wall pressure signatures were measured in real-time using wide-band Kulite miniature semiconductor transducers, with continuous digital recording (Ref. 1).

Subsequently, a synchronized sampling system was developed which allowed programmable digital data acquisition from fixed instrumentation. Using this electronic "pacer", analog to digital (A/D) sampling and conversion of transducer signals was controlled. Samples could be taken at any of 128 positions between any adjacent pair of the 18 blades of the rotor, independent of the speed (Ref. 2). Case wall pressure signatures were recently obtained using synchronized sampling (Ref. 3).

The blade-element performance of the rotor blading was measured using a combination fine-wire thermocouple/pneumatic probe. However, in the studies reported by Dodge, (Ref. 4) and Hawkins (Ref. 5), negative values of blade element loss

were derived from the impact pressure and temperature measurements, and the question of whether the pneumatic probe was correctly averaging the flow from the rotor was raised.

The present study therefore focused on the measurement of impact pressure in a pulsating flow environment. Previous studies elsewhere had shown that pneumatic probe errors in pulsatile air flow could be as large as 19% (Ref. 6). The purpose here was to measure probe response for particular probe geometries, and to derive, if possible, a correction for the pneumatic probe measurements made in the compressor.

Using a pulsatile flow generator consisting of an air jet periodically chopped by holes in a rotating plate, the steady (averaged) measurements of impact pressure registered by existing and proposed pneumatic probe configurations were compared over a wide range of frequencies with the time integrated output of a Kulite transducer probe.

The Kulite probe was then installed in the transonic compressor. The waveform obtained from the compressor was compared with that obtained in the pulsatile flow generator. It was concluded that, for the present conditions of the compressor tests, the correction required to be made to the impact probe measurements downstream of the rotor was small. Alternate explanations for negative losses were then examined.

Section II describes comparative tests of the Kulite and pneumatic probes carried out using the pulsatile flow generator. In Section III the results of measurements obtained in the transonic compressor are given; a discussion of the results and considerations of the loss coefficient question

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follows in Section IV. Conclusions are given in Section V.

While the motivation for the present study was the resolution of the question of negative loss coefficients, additional experience relevant to the problems of interpreting Kulite probe measurements was gained, and this is reported in Appendix A. The design and construction of the Kulite impact probe is given in Appendix B. Modifications and improvements which were effected to instrumentation and equipment are described in Appendix C, and computer programs are documented in Appendix D.

II. MEASUREMENTS OF PNEUMATIC PROBE RESPONSE IN PERIODIC FLOW

A. PROBES

The indicated total pressure of two existing and three proposed probe configurations were compared with the time-averaged output of a simple impact probe containing a Kulite CQ-052-25 subminiature transducer in the tip. The probes are shown in Figures 1a through 1e. A brief description of each pneumatic probe follows.

1. <u>United Sensor YC-120</u>:

A three hole probe 17.5 inches in length, similar in construction to the five hole probe described in Ref. 7, and frequently used in compressor tests at N.P.S.

2. <u>Dodge Probe</u>:

A four sensor pneumatic probe with integral thermocouple described in detail in Ref. 4.

3. <u>Straight-tubing Probe 1</u>:

A five inch long piece of stainless steel tubing with an O.D. of 0.072 inches and an I.D. of 0.054 inches.

4. <u>Straight-tubing Probe 2:</u> A twelve inch long piece of stainless steel tubing with an O.D. of 0.0355 inches and an I.D. of 0.023 inches. This probe was designed according to the criteria given by Grant in Ref. 6.

5. <u>Pin-hole Probe</u>:

A five inch long stainless steel tube with an O.D. of

0.072 inches and I.D. of 0.054 inches. A 0.036 inch deep
plug was inserted in the sensor tip and drilled through
the center 0.0045 inches in diameter, with the inner end
tapered approximately 45°.

B. APPARATUS AND EXPERIMENTAL PROCEDURE

A fluctuating (periodic) flow was produced using a mod-
ification of the flow generator described in Ref. 1. The
flow generator and the probe mounting arrangement are shown
in Fig 2. Regulated air was delivered through a settling
chamber to a 0.2 inch diameter jet. An interrupter wheel
nine inches in diameter and driven by a speed-regulated
electric motor, was mounted directly above the jet. The
wheel had 60 holes, each .422 inches in diameter, around the
periphery at the radius of the air jet. Thus, on rotation,
the frequency of the interrupted flow in C.P.S., was equal
to the wheel rpm. The ratio of the hole width to the plate
width between holes was 8.3 to 1.

The probes were mounted in adjustable jigs. Taper pins
were used to insure repeatability and accuracy of alignment.

The pneumatic probes were connected through twenty feet
of tygon tubing to a water manometer and scanivalve trans-
ducer. A regulator was used to hold the supply pressure,
measured in the settling chamber, constant to within 0.2
inches of water.

The Kulite output was balanced and amplified, then fed
to the Real-Time data acquisition system described in Ref.
1 and 2, and shown in Fig. 4. The probe was calibrated by

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applying air to the jet without interrupter wheel rotation. The output voltages obtained at several air pressures were plotted and a least-squares routine was used to fit a linear curve through the points. A sample calibration curve is shown in Fig. 5.

Four methods of obtaining the data, and an average of the data form the Kulite probe were used:

1. In the"Free-Run" mode, of the A/D converter, data samples were taken at ten microsecond intervals for the desired number of samples. (1681 samples were used in the tests described here). The time average was then taken to be the numerical average of the 1681 samples.

2. Data samples were taken in the "Free-Run" mode and were subsequently "repacked" into a single waveform using the measured frequency of the periodicity. A precise meas- urement of the frequency was required, otherwise a distorted waveform resulted. The average was evaluated using the trapezoidal rule.

3. Synchronized sampling of data, (described in Ref. 2), across a selected pair of holes, using 255 sample points per pair, and 7 to 15 samples per point.

4. Synchronized sampling at a specified location in each hole pair, with 7 to 15 samples per location. The sampling point was then stepped in 255 increments to, in effect, sample two complete revolutions of the wheel.

Since the sampling points were at equally spaced intervals in the last two methods, a numeric average was used in both cases. The last two methods used the "pacer" described in

Ref. 2.

Throughout the tests the total pressure was maintained constant at 65 inches of water, and the wheel speed was varied from zero to 8000 rpm.

C. RESULTS

Typical waveforms reconstructed from data acquired from the Kulite probe in the pacer mode at four different frequencies are shown in Figures 6 through 10. Waveforms agreed qualitatively with oscilloscope presentations. Comparisons of the average pressure versus frequency for all probes evaluated are shown in Fig. 10 and Fig. 11. The average for the Kulite probe was taken to be that obtained in the "Free-Run" mode, using 1681 samples at ten microsecond intervals. Figures 12 and 13 show the pressure averaging errors of the pneumatic probes with respect to the Kulite probe over the range of frequencies tested.

The accuracy and repeatability of the pneumatic measurements were estimated to be better than $\pm$ 0.3 inches of water. The accuracy and repeatability of the data acquired using the Kulite probe were estimated to be $\pm$ 0.8 inches of water. Additional comments on the accuracy of the Kulite measurements are given in Appendix A.

III. MEASUREMENTS IN THE COMPRESSOR

A. TRANSONIC COMPRESSOR

The transonic compressor is shown in Fig. 14. It is
driven by an air turbine drive unit capable of supplying
450 horsepower at 30,000 rpm to the compressor. When
operating at the design point, the relative Mach number at
the compressor rotor blade tip is 1.5. The flow rate is
controlled by an electro-hydraulic rotating throttle plate
located in the inlet duct, which also houses a filter and
flow measuring nozzle. An Allis-Chalmers multi-stage axial
compressor supplies the turbine drive air. A complete
description of the test facilities is contained in Ref. 8.

In the tests reported here the compressor was operated
at about 50% speed (15,230 rpm) at two different flow rates.

B. EXPERIMENTAL PROCEDURE

The Kulite impact probe (Fig. 1a and 1b) was designed
to be inserted through a 3/4-inch diameter plug in the
compressor case wall between the rotor and stator blade
rows. The design provided for rotation in yaw about the
probe tip and translation radially from hub to tip. Details
of the construction are given in Appendix B.

The Dodge combination probe (shown in Fig. 1c) and the
Kulite probe were installed at the same axial location be-
hind the rotor, and separated peripherally by 90°.

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The desired mass flow and speed were set and allowed to stabilize. The combination probe was rotated to balance the side pressures P_2 and P_3, and the yaw angle was recorded. The Kulite probe was then rotated to the same yaw angle and depth as the combination probe.

An on-line calibration of the Kulite probe was performed. This procedure, which is discussed in Ref.1, involved applying several different steady reference pressures to the Kulite pressure reference tube. The probe output voltage was linearly proportional to the pressure differential across the semiconductor diaphragm of the transducer (to which a strain gauge is fused). A least-squares fit to a linear curve was used to determine the slope of the calibration. In order to derive the intercept of the calibration curve, it was assumed that the indicated total pressure of the combination probe was the correct time-average impact pressure.

The probe immersion depth was varied in four steps. Data samples were taken from the Kulite probe at two different flow rates at a fixed speed of 15,150 rpm. Indicated total pressure downstream of the rotor and total temperature change across the rotor were recorded from the combination probe. Fixed instrumentation and off-line computer programs were used to determine the overall compressor performance and reference data for the probe measurements.

C. RESULTS

Kulite probe data were recorded at four points. The test conditions for three points are shown in Table III-1. Also included in Table III-1 are the quantities $P_{t1}(T_{t2}/T_{t1})^{\gamma/\gamma - 1}$

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and $T_{t1}((P_{t2}/P_{t1})^{\gamma-1/\gamma}-1)$, evaluated from the combination
probe measurements. These quantities are the isentropic
(zero loss) values of P_{t2} (for the measured T_{t2}) and the
isentropic value of the temperature rise (for the measured
P_{t2}) respectively. The differences between the isentropic
and the measured values of P_{t2} and ΔT_t are shown in Table
III-1 and are interpreted as the minimum error in measure-
ment required to produce negative values of the loss coeff-
icient.

The impact pressure distribution for point 1 is shown
in Fig. 15. For the test conditions at this point the
compressor was operating near optimum efficiency at 50%
design speed. The impact pressure distribution for point
4, obtained at the same compressor speed but at a flow rate
close to stall, is shown in Fig. 16.

Qualitatively, the recorded waveforms agreed well with
oscilloscope observation, however, as the compressor flow
rate was reduced (from point 1 to point 4), the part of the
waveform from the flow near the blades became progressively
more unsteady. At point 4, about 50% of the waveform was
violently unsteady, while the other 50% was steady. This
can be seen in the noise level imposed on the distribution
shown in Fig. 16.

IV. <u>DISCUSSION</u>

A. MEASUREMENTS USING THE FLOW GENERATOR

In appraising the results shown in Fig. 10 and Fig. 11
it is important to realize first that the general shape of
the curves reflect changes that occurred in the periodic
flow from the flow generator as the speed was varied. These
changes can be seen in the examples of the waveforms given
in Figs. 6 through 9. It can be seen in these figures that
as wheel speed was increased the peak pressure, the minimum
pressure, and the general shape of the waveform changed in
what appears to be an irregular way. It is noted, however,
that the waveforms were repeatable at any fixed wheel speed.

The changes in the waveform cannot be explained using
only the indications of the pressure probes. It was to be
expected that the flow field generated by a free jet which
is periodically interrupted would not be easily predictable.
An unknown variation in flow angle would certainly be pro-
duced. However, the qualitative changes in waveform which
occurred at different frequencies were not anticipated. At
low wheel speeds the peak pressure was close to, but less
than, the jet supply pressure (Fig. 6).   At higher speeds
(Fig. 7) there were two peaks which were greater than supply
pressure, indicating addition of energy. At even higher
speeds (Fig. 8) the first peak value was larger while the
second was reduced. At the highest speed shown, (Fig. 9)
the amplitude of both peaks declined and the waveform became
flatter.

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It is the time integral of the pressure sensed by the Kulite probe that is shown in Fig. 10 and Fig.11. In view of the observed changes in the waveform, the variation of this time average with frequencies is not questioned. Also, the general trend of the average pressures, measured by all the probes which were tested, is in agreement with the Kulite probe measurements. Therefore, the Kulite probe measurements were accepted as a measure of the true time average pressure, and the "error" in the average pressure sensed by the pneumatic probes was examined.

The errors in pressure averaging for the multiple sensor probes and for the straight tubing probes are shown in Fig. 12 and 13, respectively. The results shown are the difference between the Kulite and the probe average pressure divided by the Kulite average (gauge) pressure. It is immediately evident that while the magnitude of the averaging errors for the different probes varied, the dependence of the error on frequency for all probes was qualitatively similar. Moreover, while there was a sharp change in the average pressure between 4kHz and 4.5 kHz resulting from changes in the waveform, the variation of the averaging error varied smoothly in this range.

The variation of the averaging error with frequency was investigated by Krause et al. (Ref. 9) for simple impact probes in a pulsatile air flow having nearly a square wave shape. Krause found that the error in averaging depended on wave amplitude, the average pressure, and the frequency.

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He also found "resonances" such as are evident in the results shown in Fig. 12 and Fig. 13, which he reasoned were due to standing waves in the measurement volume. In the present experiments using the flow generator, changes in these parameters could not be controlled independently. The results must therefore be viewed as a comparison between the different probes and should be used only to judge the accuracy of probe measurements previously obtained in the transonic compressor, and to guide in the selection of probes for future measurements.

It is seen in Fig. 12 that below a frequency of about 4 kHz, the averaging errors of both the combination probe and the United Sensor probe were fairly small (less than 5%). However, the "resonance" (following Krause) between 4 kHz and 6 kHz caused a maximum error of up to 14% for the combination probe and 12% for the United Sensor probe. Since this is the range of frequencies experienced in the transonic compressor, and since the resonance is affected by the measurement volume, the response of these probes needs to be examined over a range of volumes, in an effort to move the resonance out of the operating speed range of the compressor. If this were done, it appears that the correction to be made to the probe readings would be small.

The results in Fig. 13 show a comparison of the errors for three different geometries of simple impact probes. The smallest error outside the range of resonance was given by the straight probe # 1. The pin-hole probe gave a negative error away from the resonance, resulting in the smallest

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positive error in the neighborhood of the resonance. Since
this probe had an extremely slow response time, use of a
pin-hole probe in the compressor would be less desirable
than the use of the other geometries.

An unexpected result was the pressure averaging error
for the straight probe # 2, which was designed for minimum
error following the criteria given by Grant (Ref. 1).
However, it gave a measureable error at low frequencies, and
an error greater than 30% in the range of resonance. This
probe used tubing similar to that used in the combination
probe, but was without bends and joints. Further tests
of a variety of geometries are required to properly test the
criteria that were followed in the selection of this probe.

B.   TRANSONIC COMPRESSOR

Since the compressor total pressure fluctuations and wake
width as shown in Fig. 15 and Fig. 16 were quite different
from those produced by the flow generator, a correction for
the total pressure as a function of frequency could not be
obtained for the combination probe. However, since the
magnitude of the fluctuation was small, the correction to
be applied for the test conditions of the compressor should
be minor. Although the static pressure at the probe location
was near atmospheric, the probe was sufficiently far down-
stream of the rotor, such that the fluctuations were much
smaller than had been anticipated. At speeds higher than
50% of design the impact pressure fluctuations may become
sufficiently large to warrant a pneumatic probe correction.

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The Kulite probe is clearly useful as a device to determine flow quality. It should also be capable of detecting the location of shock waves, regions of separated flow, and flutter effects in the compressor.

The Kulite probe geometry that was chosen allows better spatial resolution of the flow, and allows interference free measurements to be made closer to the compressor walls, than probes previously used in the transonic compressor.

C. LOSS COEFFICIENTS

Based on the discussion in the previous section an error in impact pressure measurement is eliminated as a possible reason for the negative loss coefficients which were evaluated and reported in Ref. 4 and Ref. 5.[1] An error in the temperature rise measurement could also result in negative losses, however the results obtained from the combination probe are in reasonable agreement with those obtained from the fixed Keil temperature probe. It should be noted that the temperature rises listed in Table III-1 for the combination probe include a mach number correction of $+0.65^{\circ}F$. This should be compared to the errors necessary to give zero losses listed in the table. A discussion of the temperature

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[1] It is noted that typographical errors exist in the equations for the loss coefficients given in Appendix D of Ref. 5. There is also an algebraic error in Eq. D (13) and the equation on page 28 of that reference where the temperature ratio, $\psi = T_{t2}/T_{t1}$, appears erroneously raised to the second power. However the use of the corrected equations would lead to losses which were even more negative in value.

measurements is given in Appendix C. A careful calibration
of the combination probe and its upstream reference probe,
with respect to a common reference probe, should resolve
this question.

V. CONCLUSIONS

The experiments using the flow generater lead to the following conclusions:

(1) The error in pressure averaging of different impact probes was measured successfully and the magnitude was found to depend on the probe geometry. The trend in the error over the frequency range evaluated,and the appearance of resonances, were similar for all probes.

(2) Further measurements are needed in order to determine the optimum (minimum error) system of instrumentation for use on the transonic compressor.

From measurements in the compressor using a Kulite impact probe, the following were concluded:

(1) Unsteady impact pressure profile measurements behind rotor blades were successfully made for the first time in the transonic compressor at the Naval Postgraduate School. Steady and unsteady regions of the flow field with respect to the rotor were detected. The Kulite probe holds considerable promise as a diagnostic tool for compressor flow fields.

(2) The waveform at the rotor exit survey station was unlike that produced by the flow generator. The error in pressure averaging at 50% design speed was assumed to be negligibly small because of the flatness and small amplitude of the impact pressure profile. However, at higher speeds a correction may be necessary.

(3) The negative loss coefficients reported in Ref.4, and Ref. 5 were not the result of incorrect pressure averaging. Other sources of error must now be investigated.

Throughout the investigations reported here, it was difficult to maintain the desired accuracy in measurements because of the effects of temperature changes on the transducer output. In future applications more effort needs to be put into measuring effects due to temperature. In a new probe design, the incorporation of a thermocouple adjacent to the Kulite tip or the parallel use of a separate thermocouple probe is strongly recommended.

TABLE III-1 TRANSONIC COMPRESSOR TEST DATA

	POINT 1	POINT 3	POINT 4
P_{t1} (in H_2O)	395.95	396.65	366.75
P_{t2} (in H_2O)	441.15	439.05	429.85
T_{t1} (Deg R)	528.98	527.93	528.35
ΔT_t (Fixed Keil-Deg F)	17.48	17.53	26.58
ΔT_t (Cor. Comb Probe-Deg F)	17.96	18.49	—
RPM	15,150	15,150	15,130
Referred RPM	14,984	14,999	14,973
Referred Flow Rate (lbm/sec)	10.35	10.35	7.46
Normalized Displacement (HUB-TIP)	0.7	0.5	0.7
Yaw Angle (Deg)	20.5	21.0	40.0

*****MEASUREMENT ERRORS WHICH WOULD GIVE ZERO LOSS COEFFICIENT*****

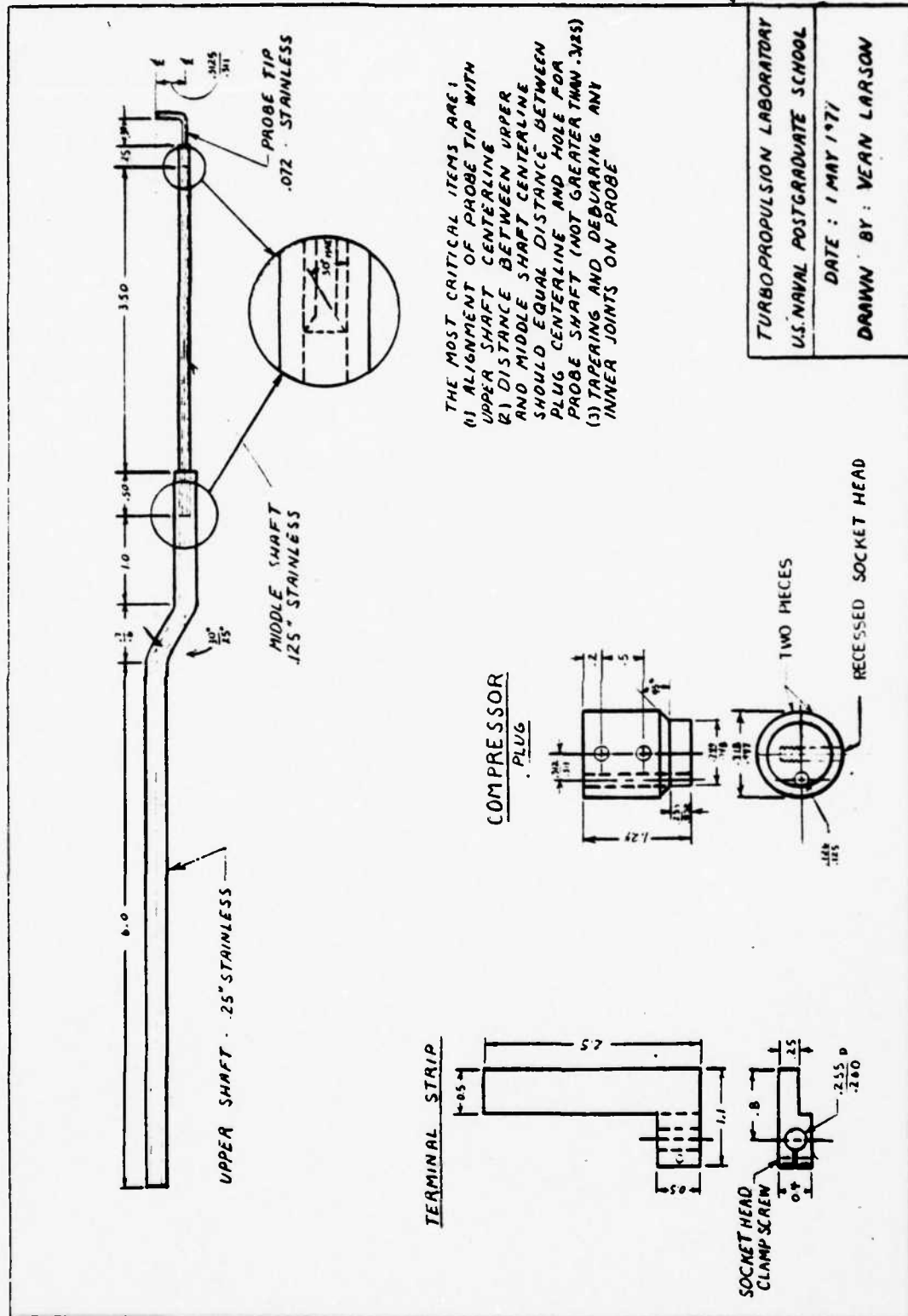|	POINT 1	POINT 3	POINT 4
$(P_{t2})_{is} = P_{t1} (T_{t2}/T_{t1})^{\gamma/\gamma-1}$	445.03	447.43	435.49
$(P_{t2})_{is} - P_{t2}$ (in H_2O)	3.88	8.39	5.64
$(\Delta T_t)_{is} = T_{t1} ((P_{t2}/P_{t1})^{\gamma-1/\gamma} -1)$	16.59	15.54	24.51
$(\Delta T_t)_{is} - \Delta T_t$ (Deg F)	-1.37	-2.95	-2.07

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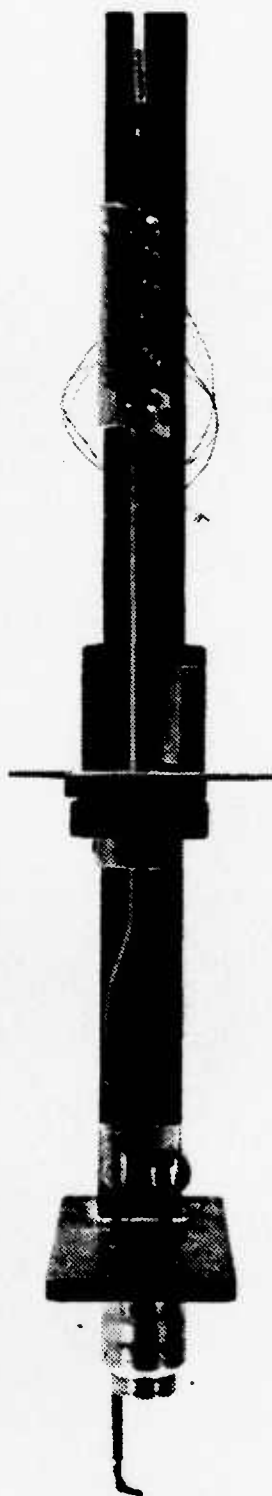Figure 1a. Kulite Transducer Probe Drawing

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Figure 1b. Kulite Transducer Probe Photograph

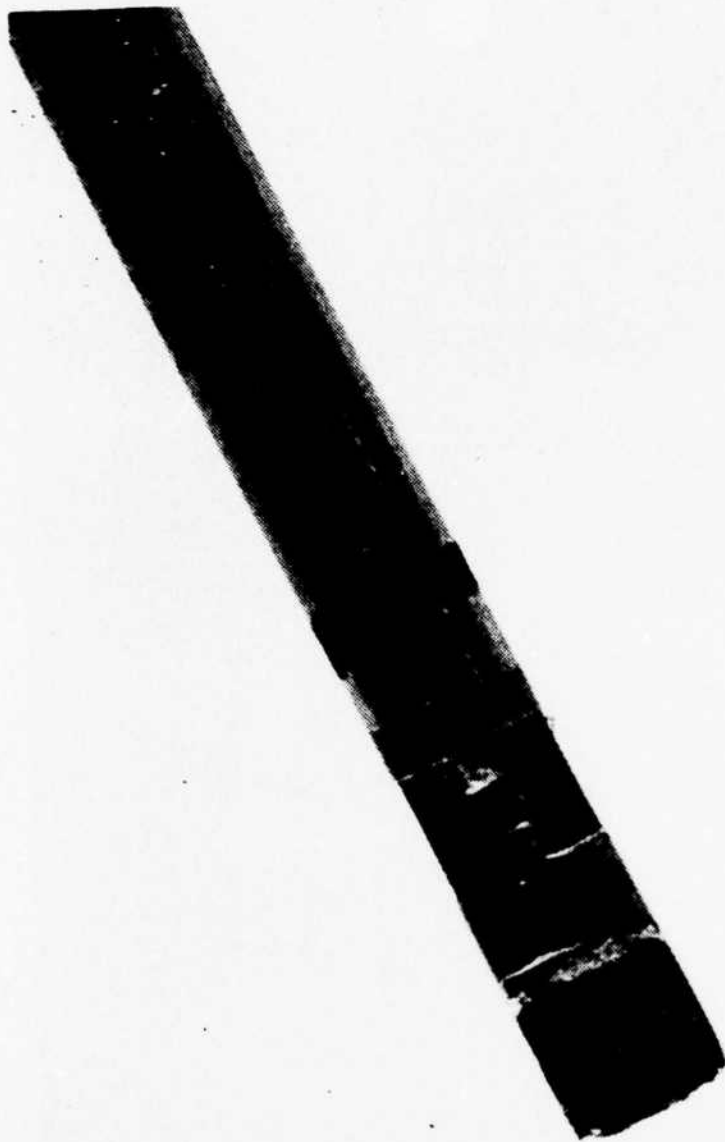Figure 1c. Dodge Combination Probe Photograph with Thermocouple Removed.
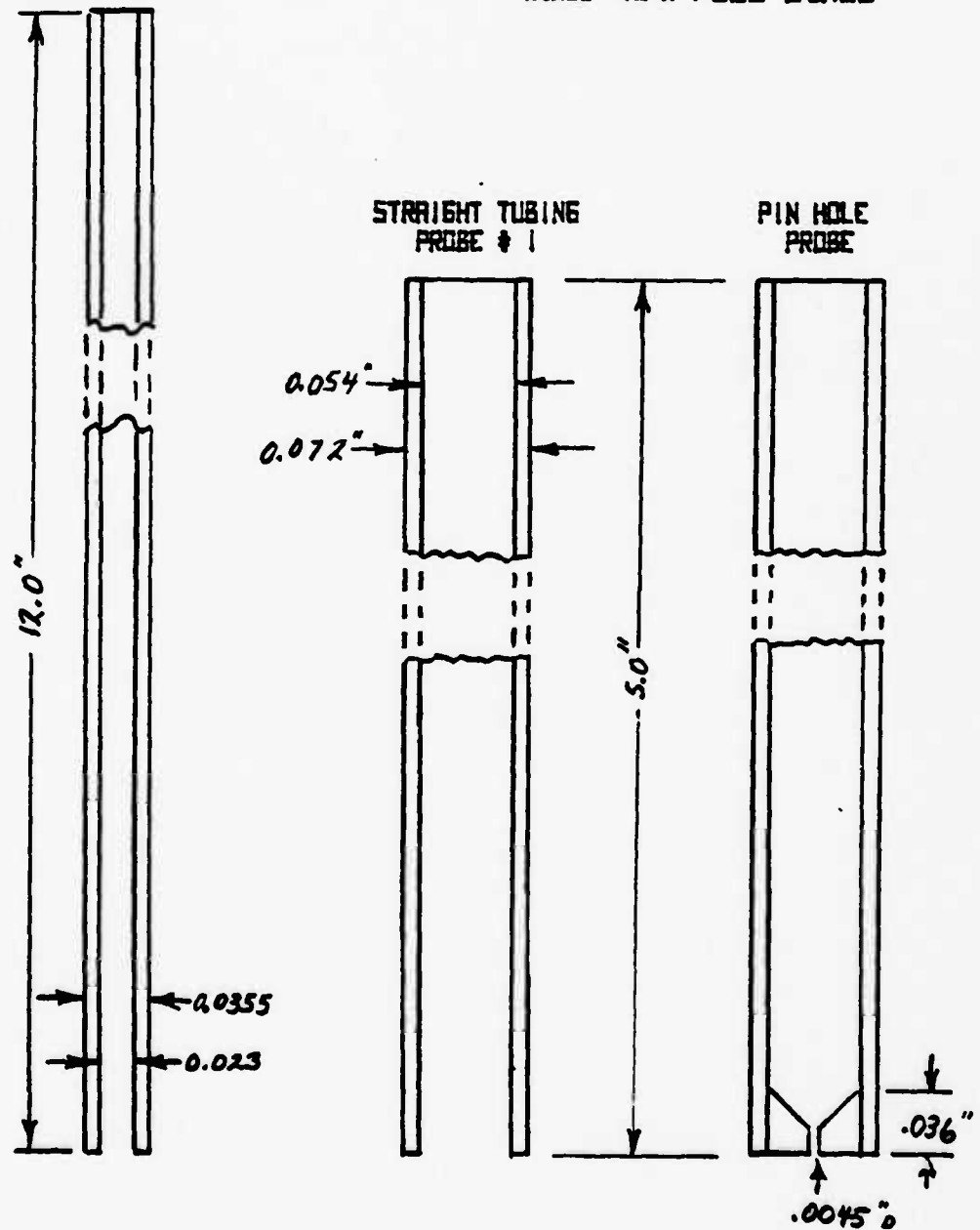
Figure 1d. United Sensor Probe Photograph

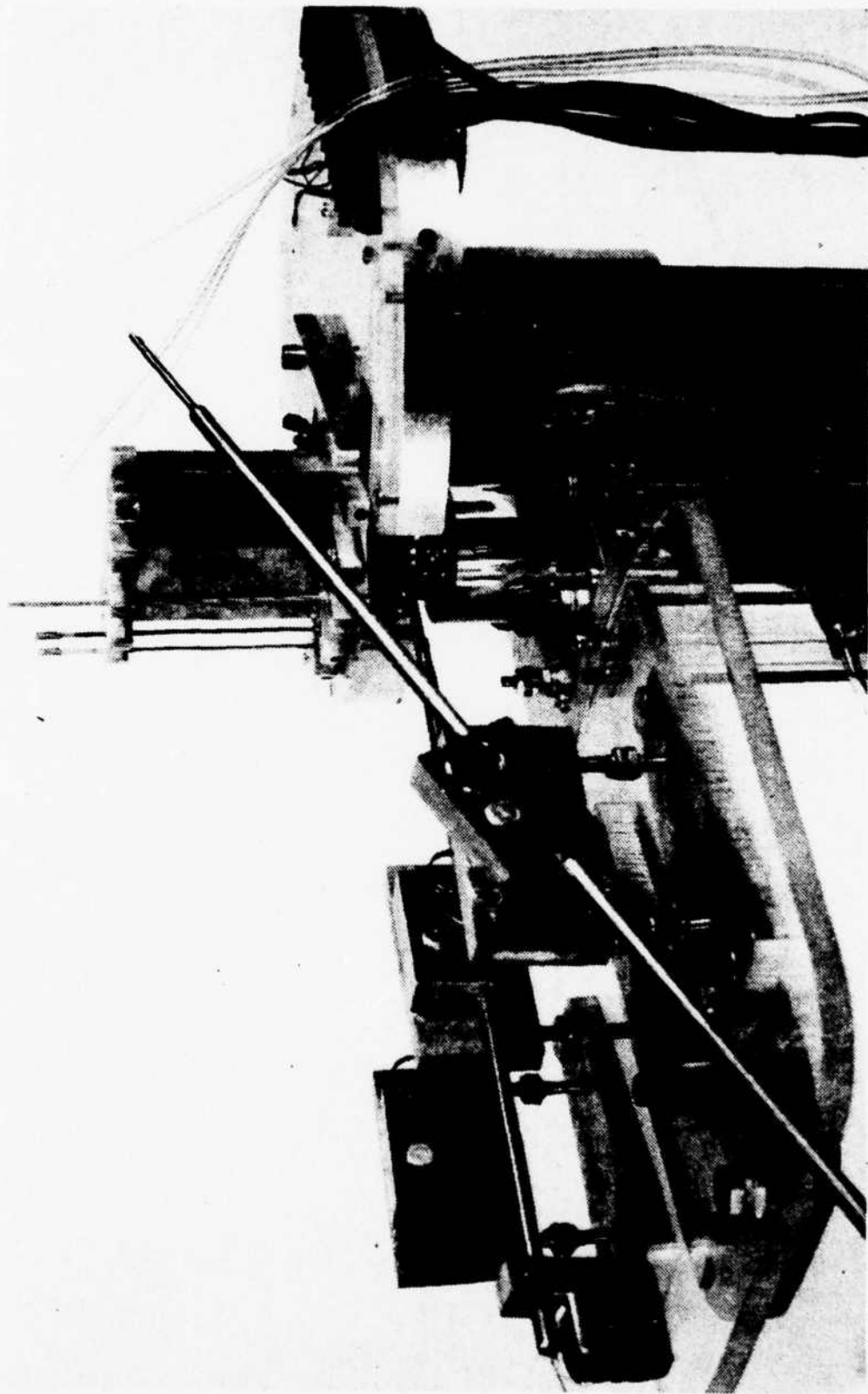FIGURE 1e.   TUBING IMPACT PROBE GEOMETRIES

Figure 2. Flow Generator and Probe Mounting Arrangement
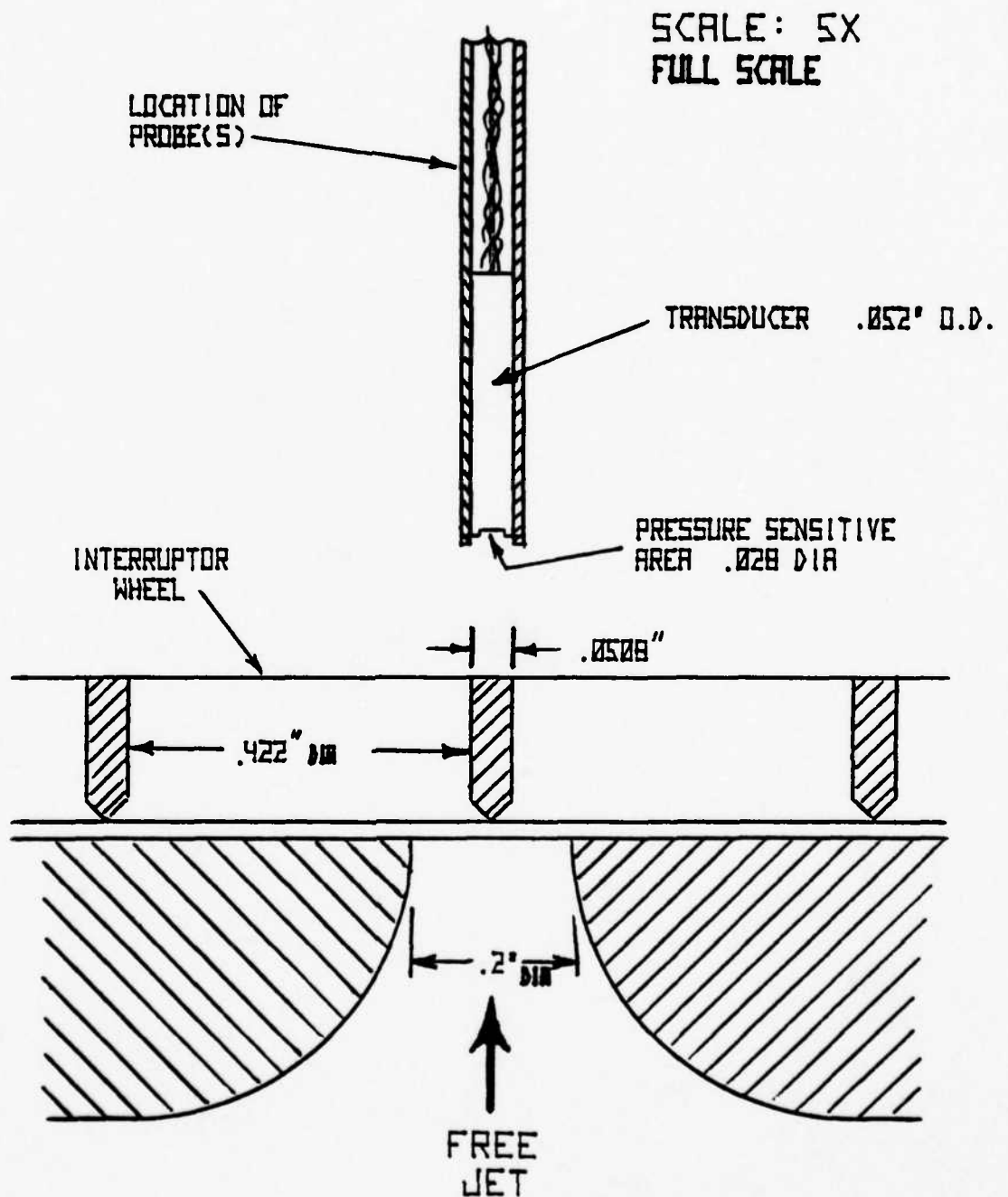
Figure 3.   Geometrical Location of the Jet, Wheel, and Probes

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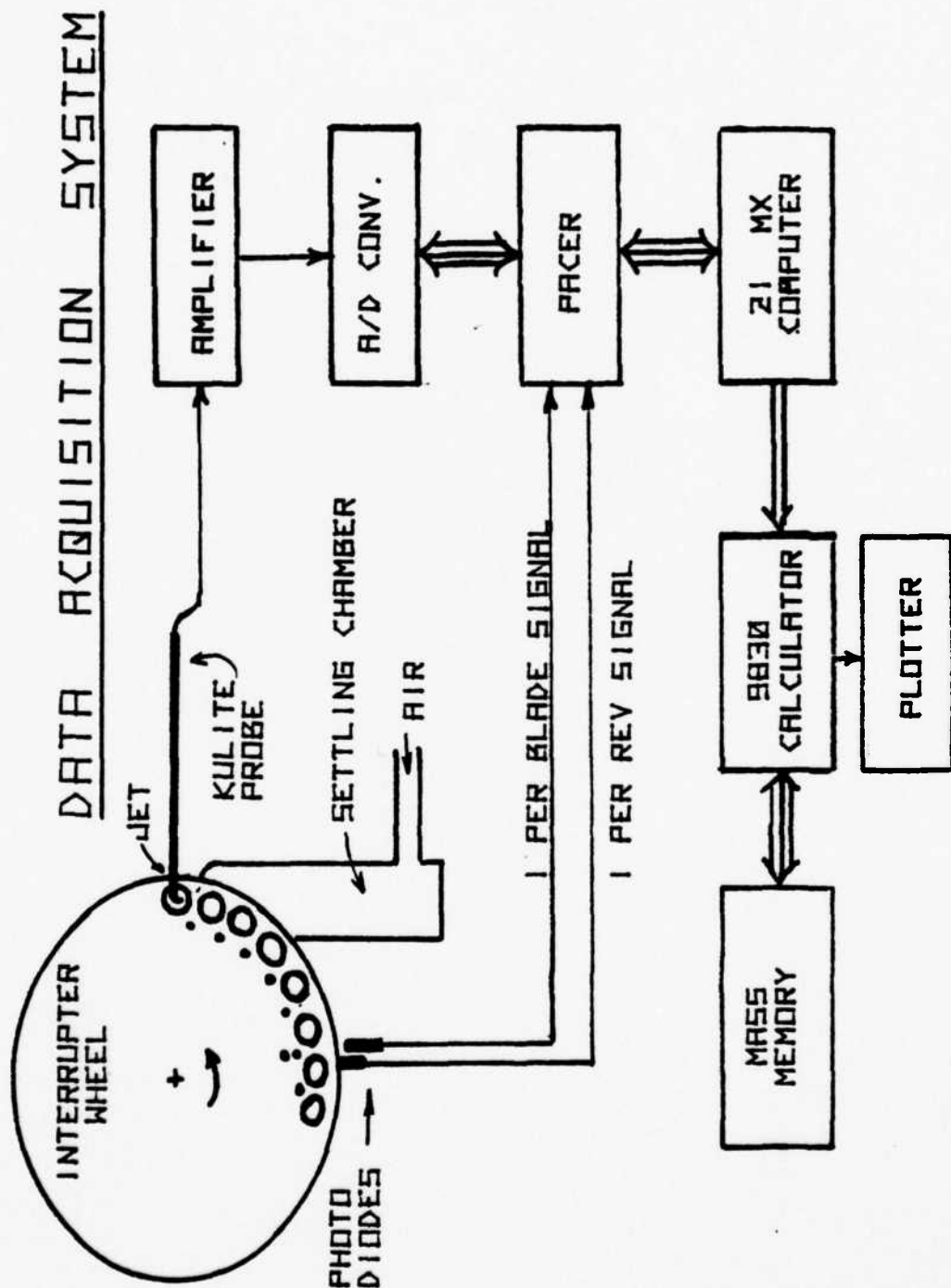
Figure 4. Flow Generator Data Acquisition System
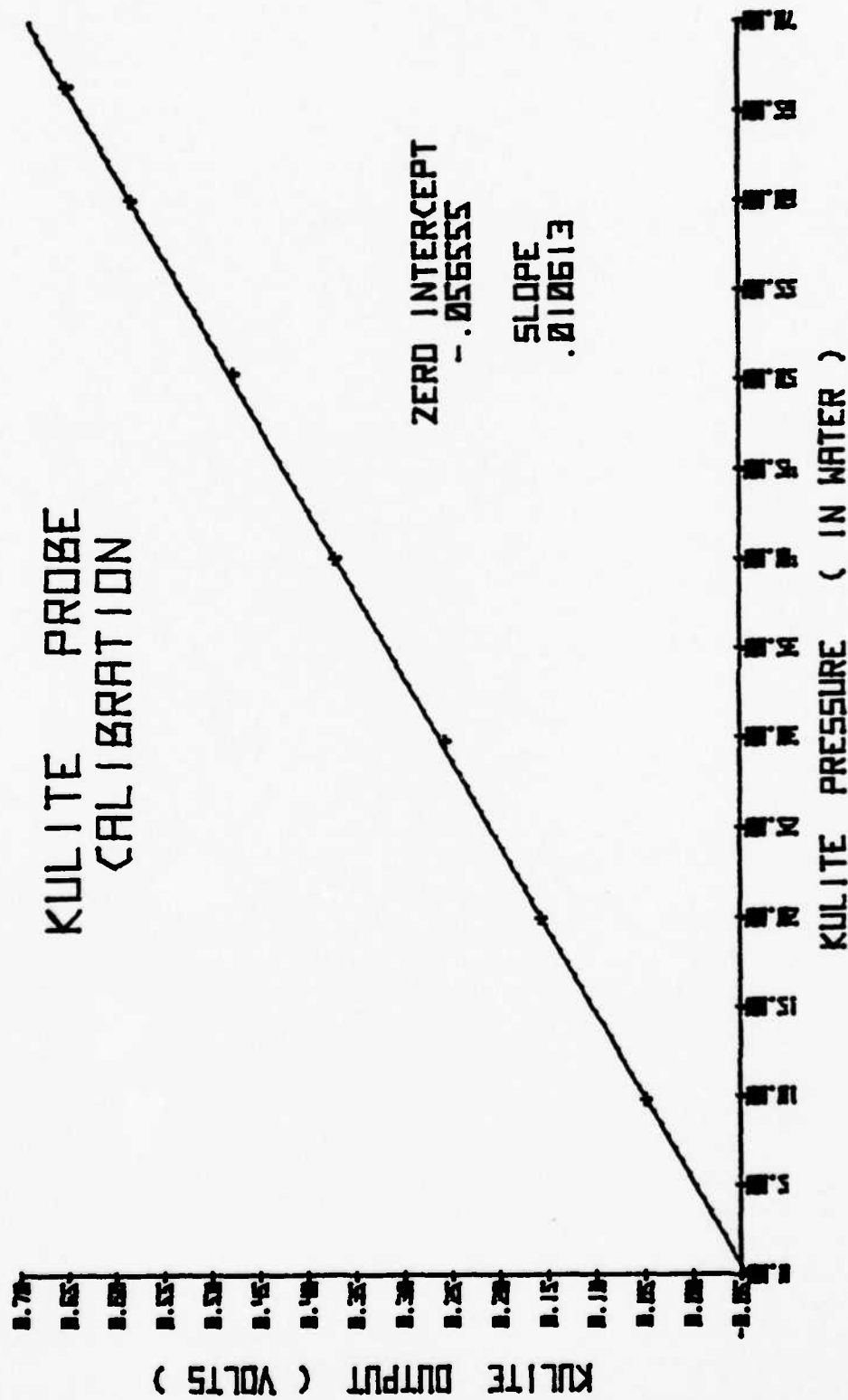
Figure 5. Kulite Probe Calibration in the Flow Generator Jet Without Wheel Rotation

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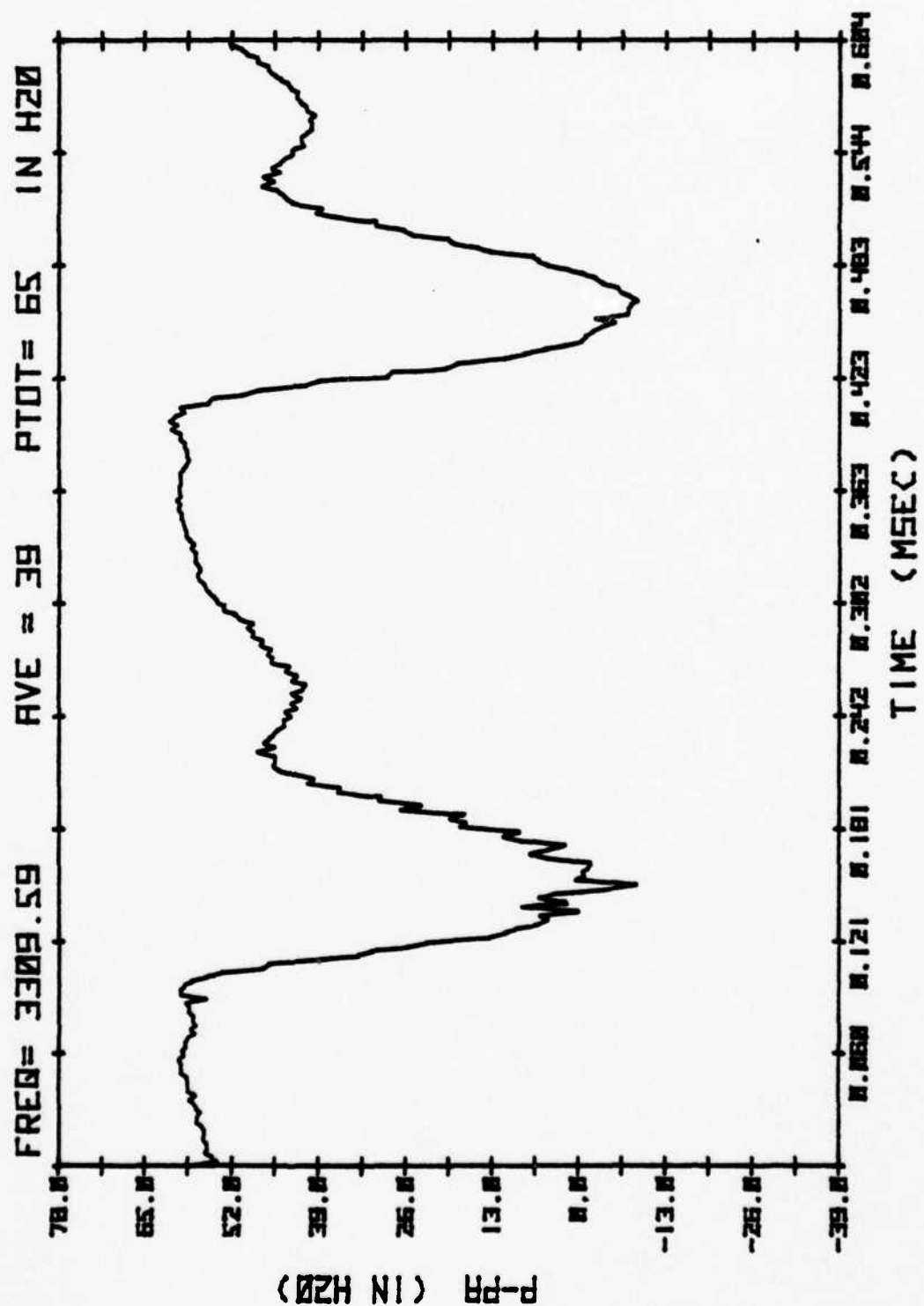
Figure 6.   Flow Generator Waveform at 3309 Hz
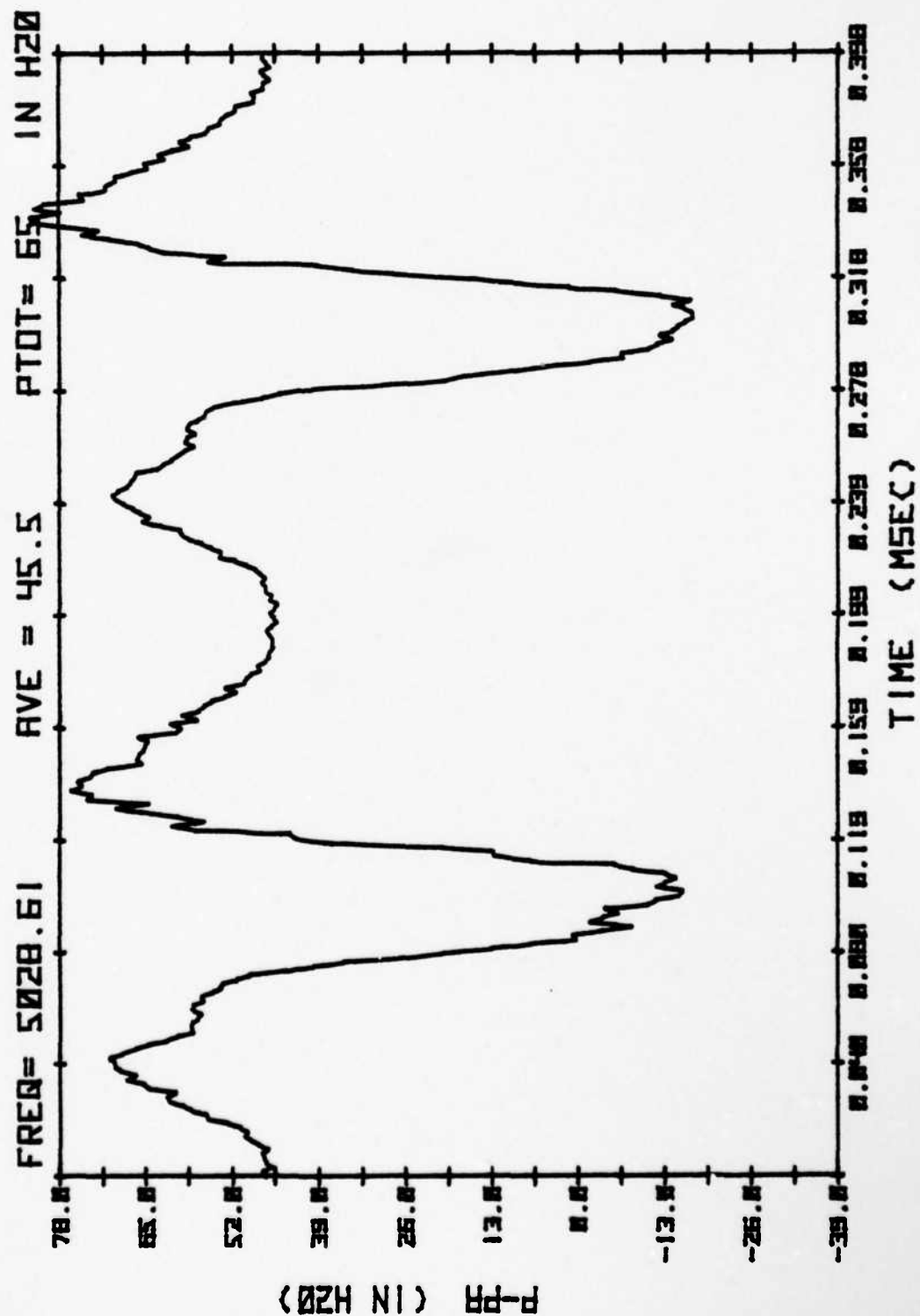
Figure 7. Flow Generator Waveform at 5028 Hz
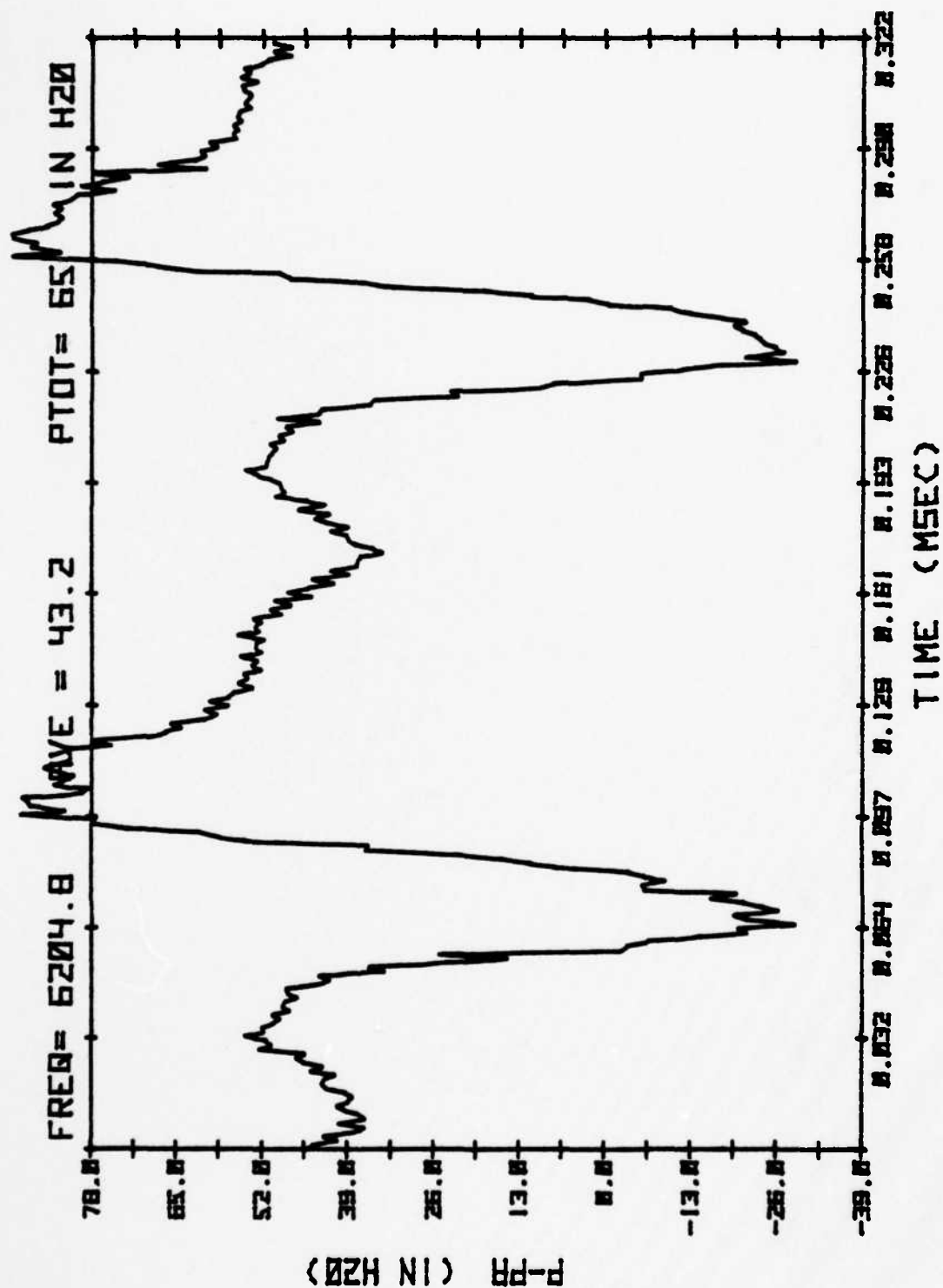
Figure 8.   Flow Generator Waveform at 6205 Hz
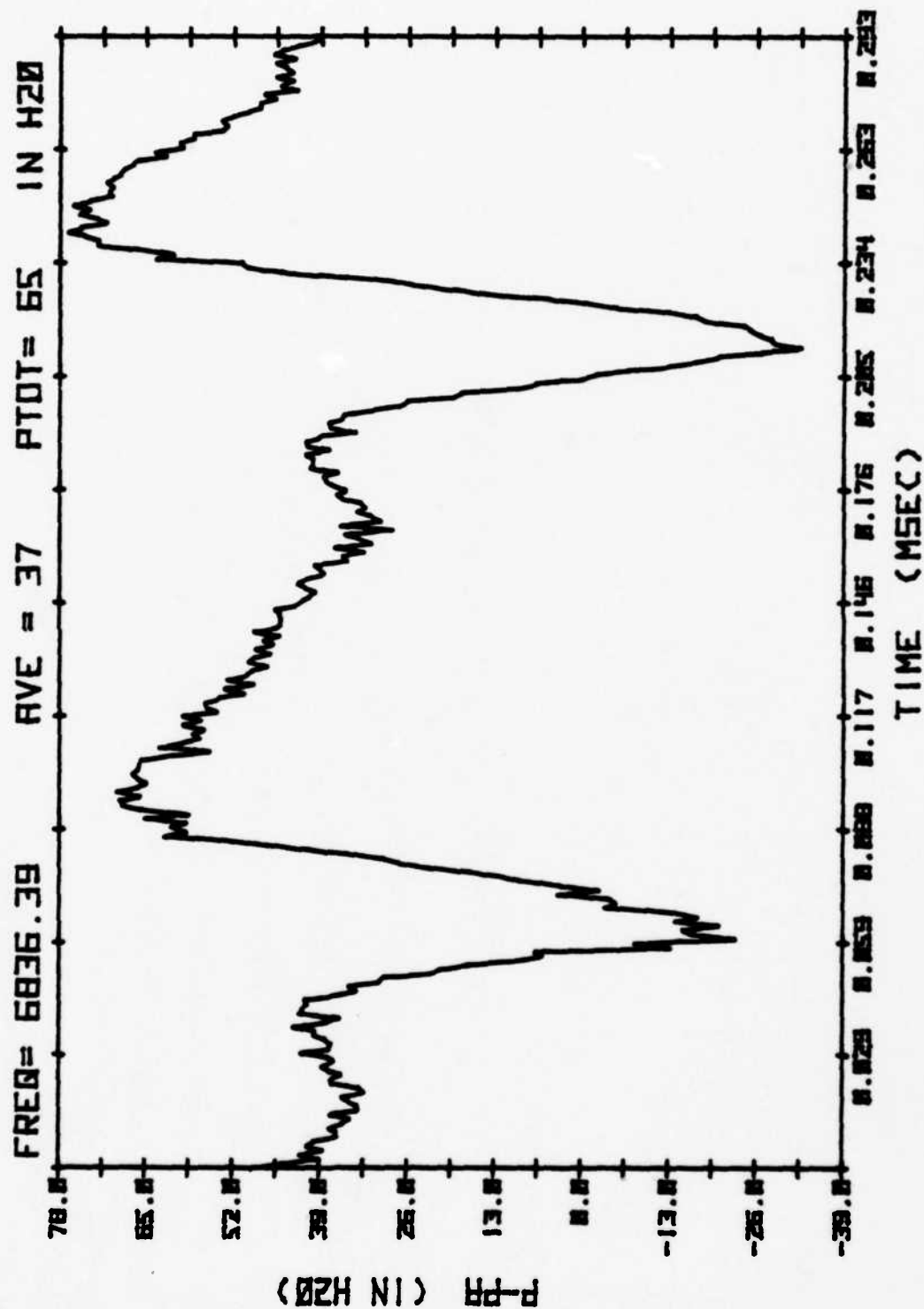
Figure 9. Flow Generator Waveform at 6836 Hz

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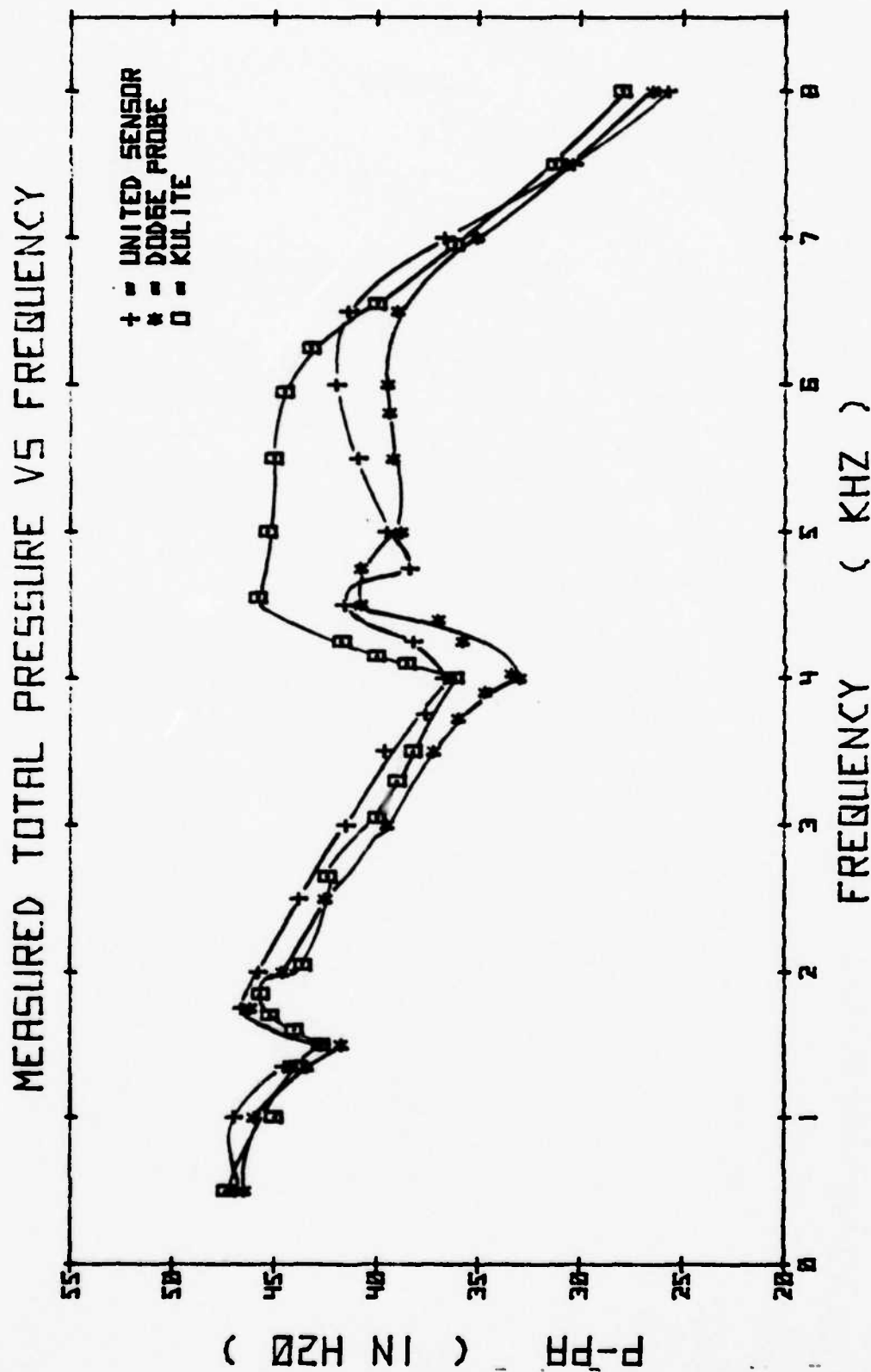
Figure 10. Comparison of Multiple Sensor Probe Response with Kulite Probe from 0.5 to 8 kHz
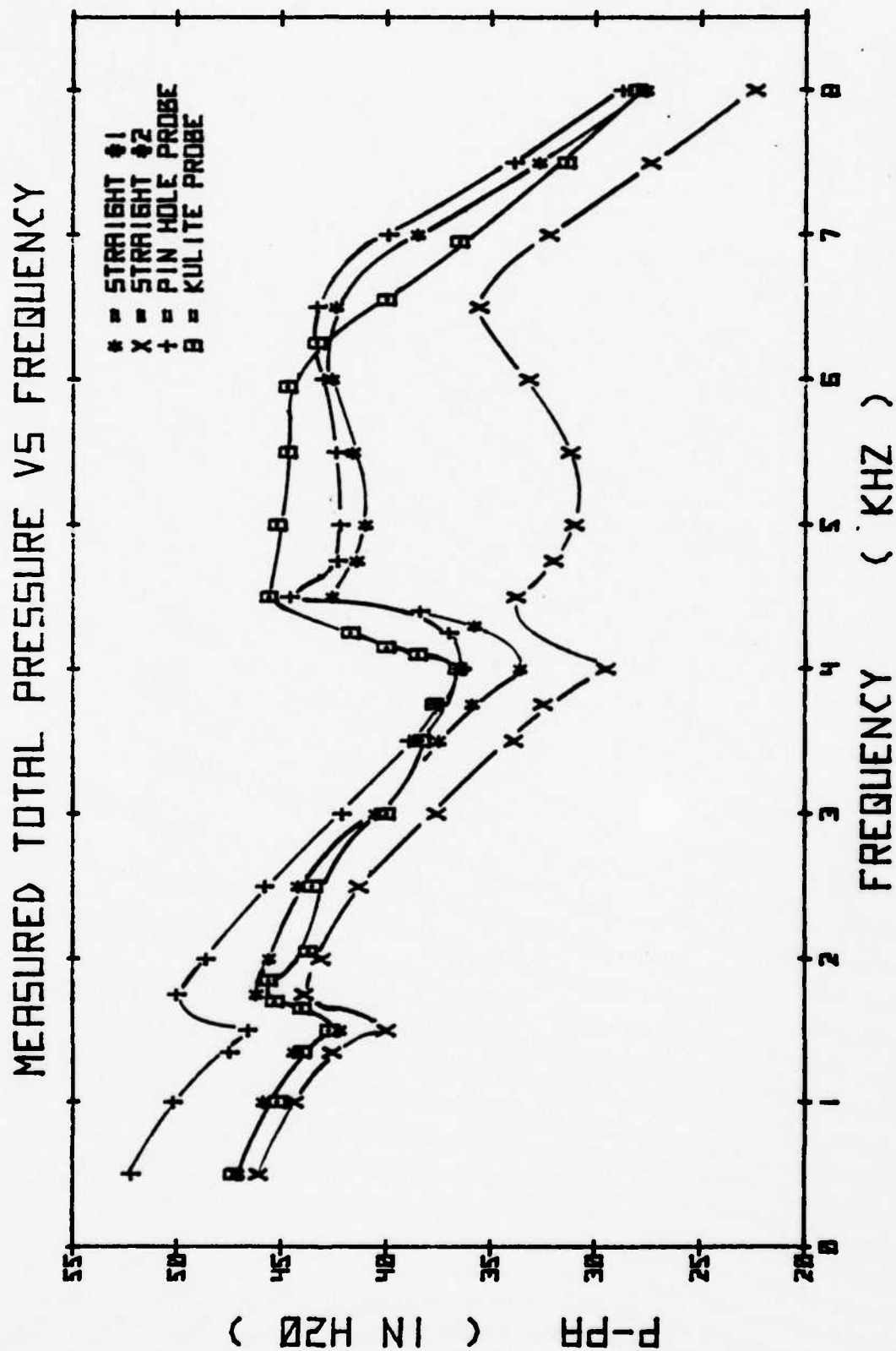
Figure 11. Comparison of Straight Tubing Probe Response with Kulite Probe from 0.5 to 8 kHz

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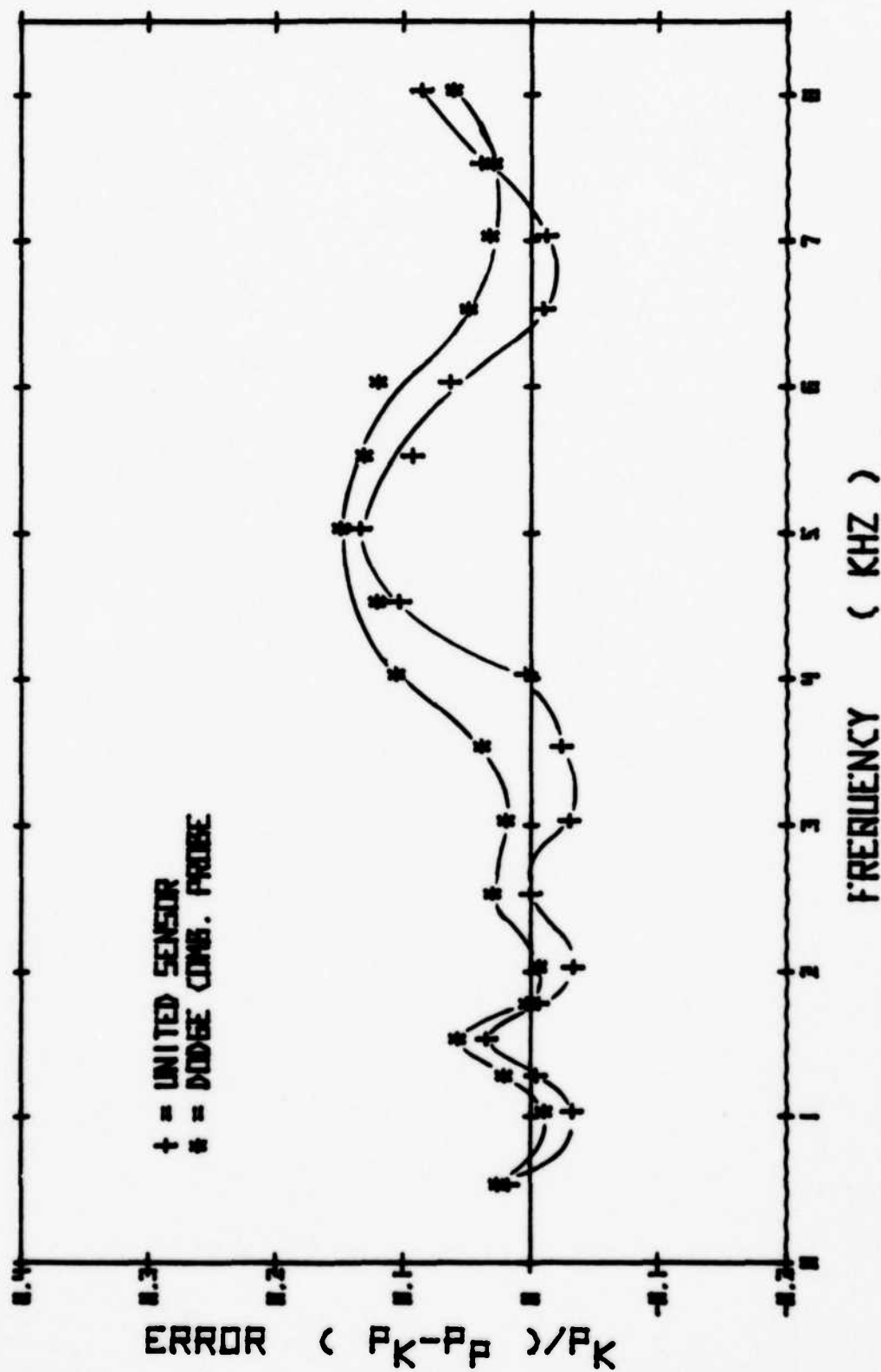
Figure 12. Error in Pressure averaging of Multiple Sensor Probes

44
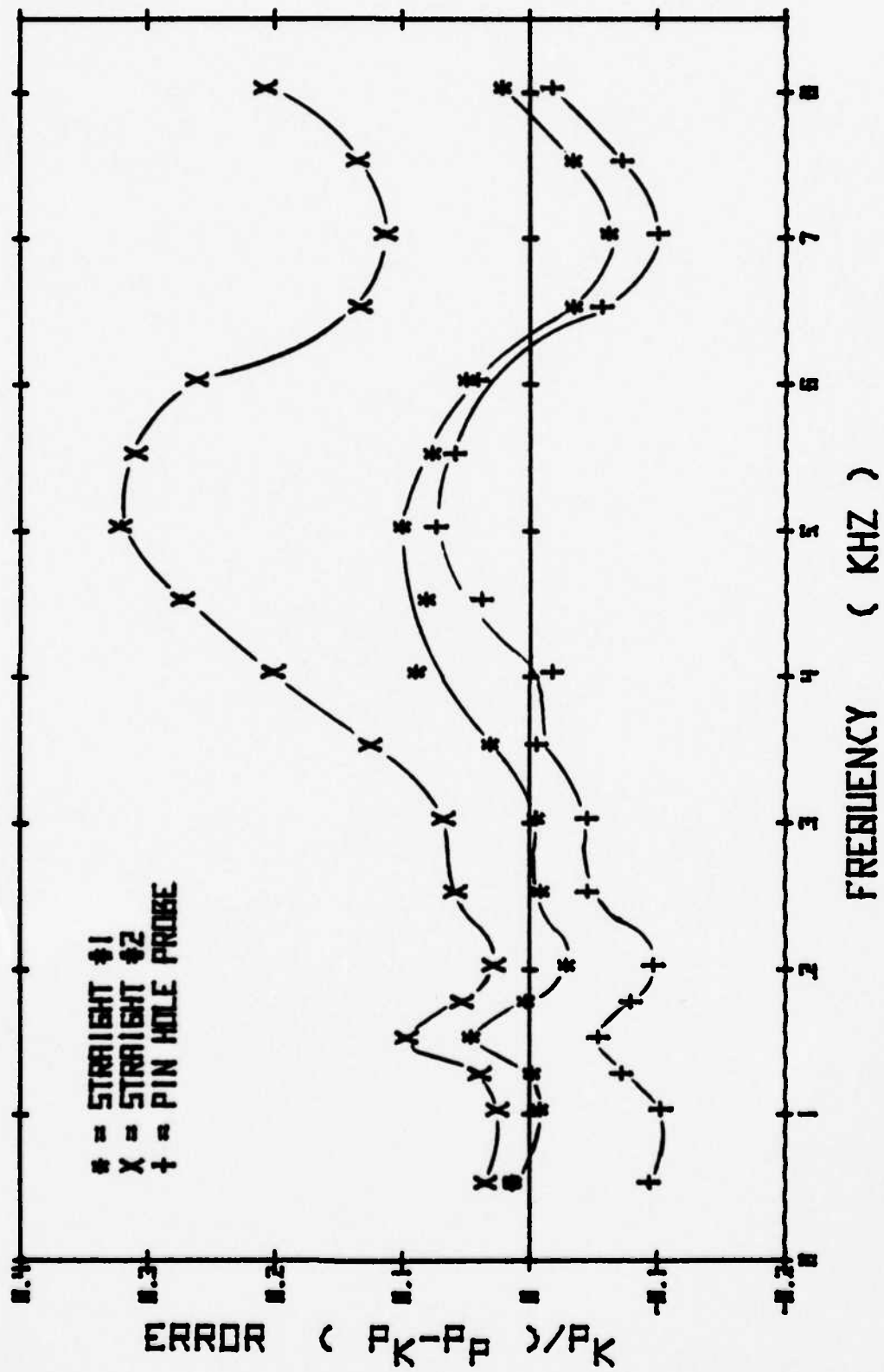
Figure 13. Error in Pressure Averaging of Straight Tubing Probes
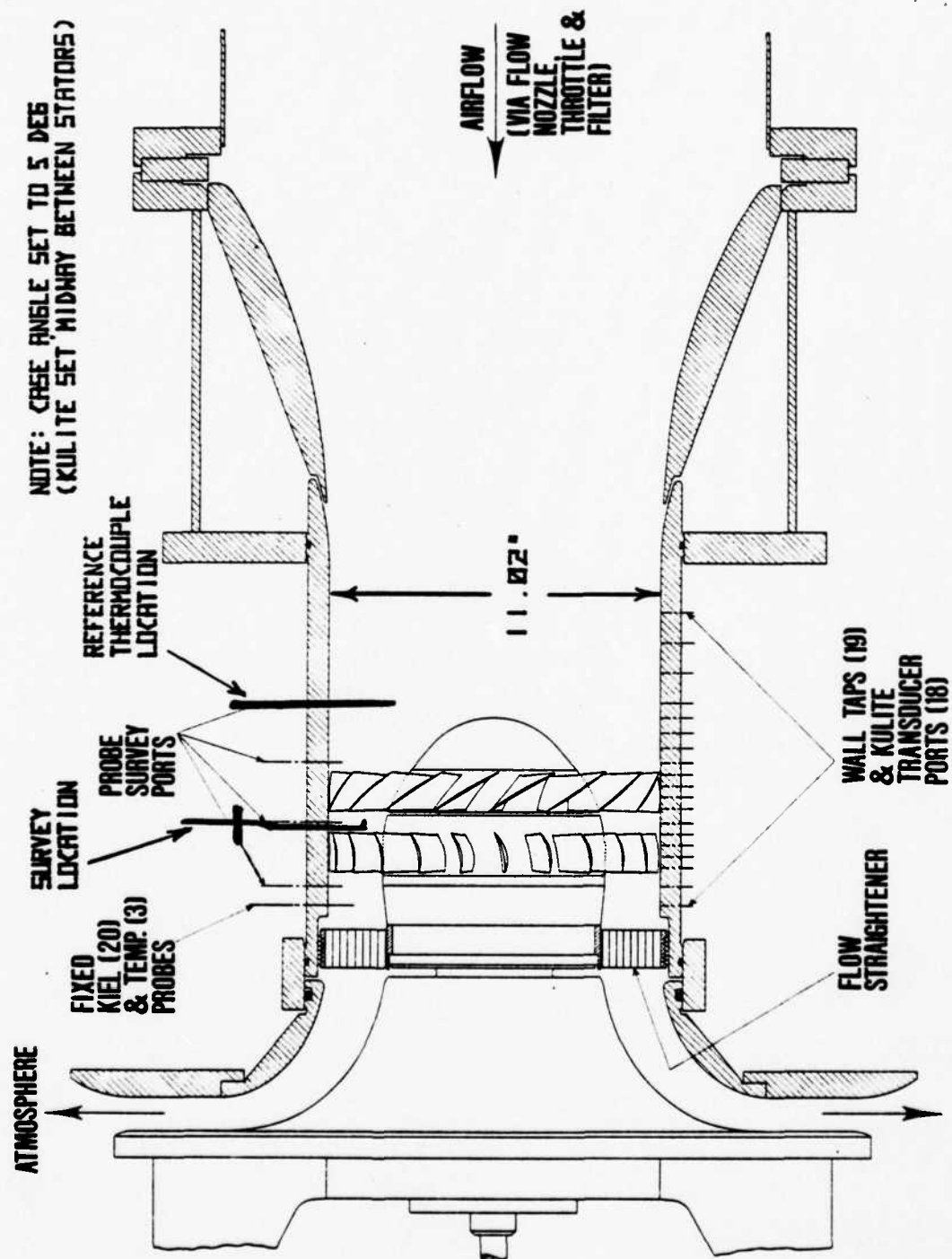
Figure 14.   The Transonic Compressor
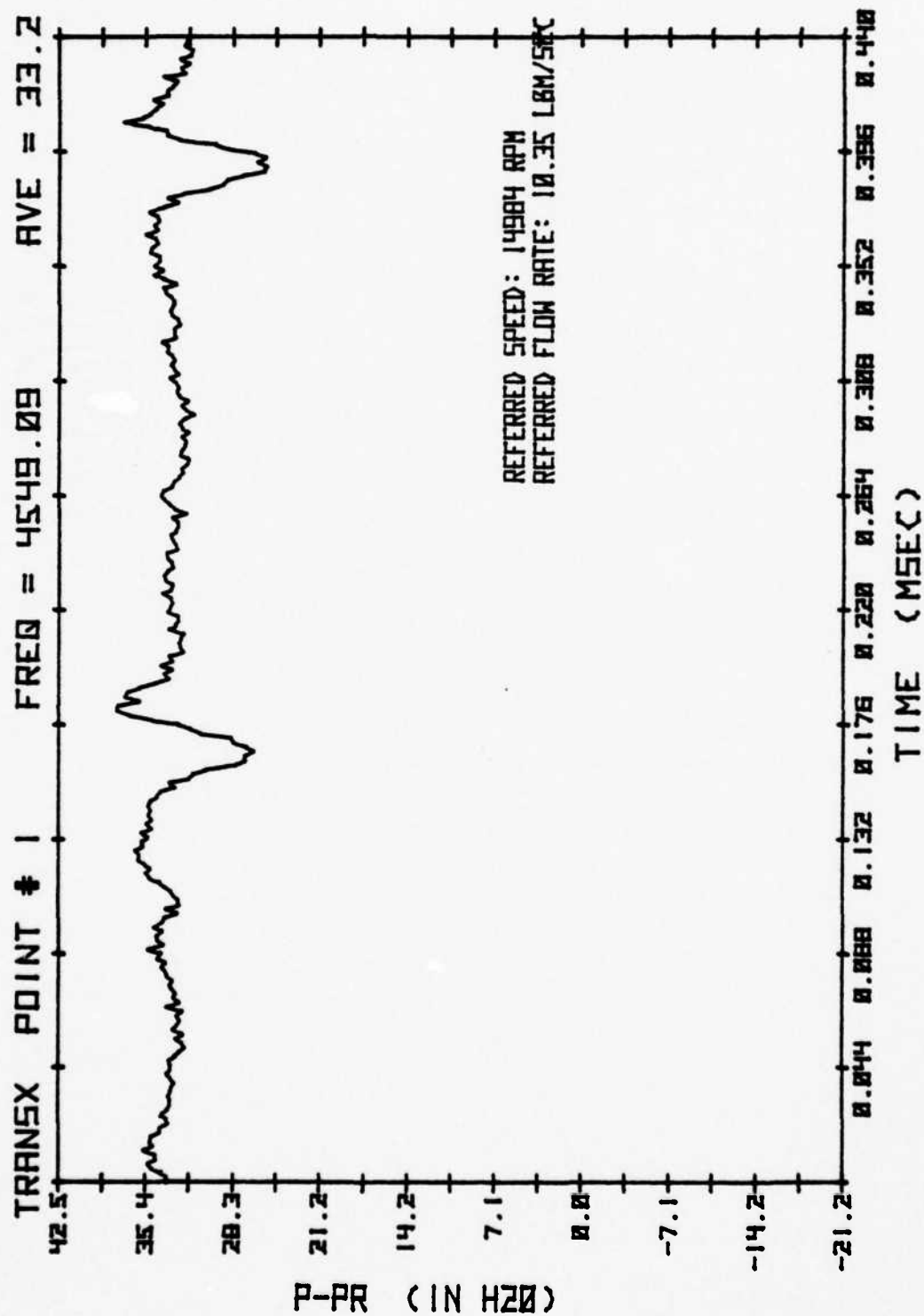
Figure 15. Impact Pressure Distribution in the Transonic
Compressor (50% Design Speed, Near Optimum
Efficiency

47
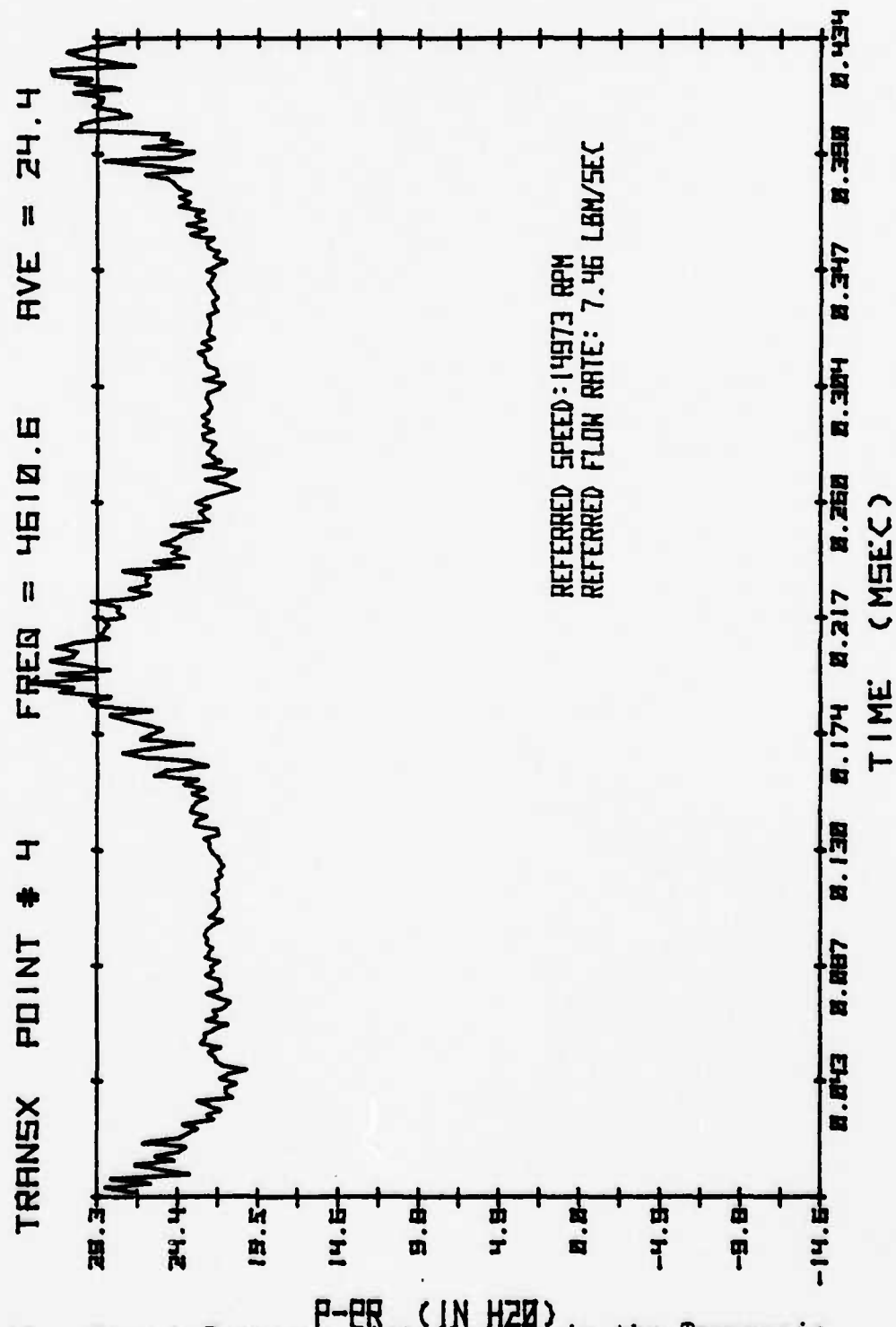
Figure 16.   Impact Pressure Distribution in the Transonic
Compressor (50% Design Speed, Near Stall)

APPENDIX A: <u>INTERPRETATION OF KULITE TRANSDUCER RESULTS</u>

Specifications for the Kulite CQ-052-25 subminiature
transducer used in the Kulite impact probe include the
following:

```
Bridge excitiation.................5V
Zero Balance Adjustment............± 5% Full Scale
Sensitivity change with temp......-3% per 100° F
No load output change with temp...± 5% F.S./100° F
Bridge output.....................-65 mV @ 25 psi (F.S.)
```

It is noted that the maximum no load output change with
temperature is 2½ times as large as that reported in Ref. 1
for the CQL-080-25 transducer used in case wall pressure
measurements.

In an attempt to measure the output variation with temp-
erature for the Kulite probe, the periodic flow generator was
used in two experiments.

In the first experiment the Kulite probe, a thermocouple
probe, and a pneumatic probe were clustered together in a
single mounting bracket. A reference thermocouple was im-
mersed in a tube of mercury set in a thermos bottle at room
temperature. With the interrupter wheel stationary, the
Kulite output and the indicated temperature differential
were recorded over a period of time. The data are plotted
in Figure A-1 (the first three points on the left).

Wheel rotation was then begun with the air supply to
the jet shut off. The output of the Kulite probe, the
temperature differential, and the suction indicated by the
pneumatic tube were recorded. From a calibration conducted

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earlier, Kulite output was nominally 10 mV per inch of water. It is noted that the Kulite output displayed on the oscilloscope was observed to have a negligible peak-to-peak amplitude compared to the D.C. component. Therefore using the assumption that the pressure registered by the pneumatic probe was the true time average of the pressure at the Kulite probe, a correction was calculated and applied to the Kulite output to eliminate the effect of pressure change. The remaining points plotted in Fig. A-1 are the results obtained with wheel rotation. In this figure increasing temperature difference (and also increasing suction) correspond to increasing wheel speed. Shown also in Fig. A-1 is the "maximum" decrease in Kulite output with temperature that could be expected from the transducer specifications.

It is noted that with no rotation the Kulite output had a slightly larger change than was expected from the specifications. However as the wheel speed was increased, and an increase occured in the suction, the dependency on temperature decreased markedly. It is not clear from this one experiment whether the change in transducer output is due to an effect of temperature and an effect of pressure separately, or whether the temperature and velocity gradients at the probe tip are important.

For the second experiment, the thermocouple probe was mounted in the jet and referenced, as before, to room temperature. In order to reproduce the test conditions used in the experiments described in Section II, the chamber total pressure was set to 65 inches of water. The temperature rise

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was then recorded as the wheel speed was increased. The
data are shown in Fig. A-2. Also shown in Fig. A-2 is the
temperature increase equivalant to the specific kinetic
energy of the wheel. It can be seen that the probe data
follows the calculated rise due to wheel speed (which rep-
resents a theoretical maximum) fairly well. However, there
is a region of zero temperature change between three and
four thousand cps which roughly corresponds to where the
average pressure measured by the different probes in Section
II exhibited a change in behavior.

From the results in Fig. A-2, it seems reasonable to
assume that during the experiments described in Section II,
the temperature of the Kulite probe was close to what would
be computed by adding the wheel specific kinetic energy to
the ambient temperature. Therefore, using the transducer
specifications, at 5,000 rpm the change in the intercept of
the calibration curve due to temperature would be approxi-
mately one inch of water. This would correspond to an error
of 1.5% of the maximum value of the impact pressure waveform,
or 2.3% of the time-average value.

In support of this argument it was noted that any Kulite
calibration shift occuring during Section II experiments was
always in the negative direction. The shift was usually 0.5
to 0.7 inches of water low.
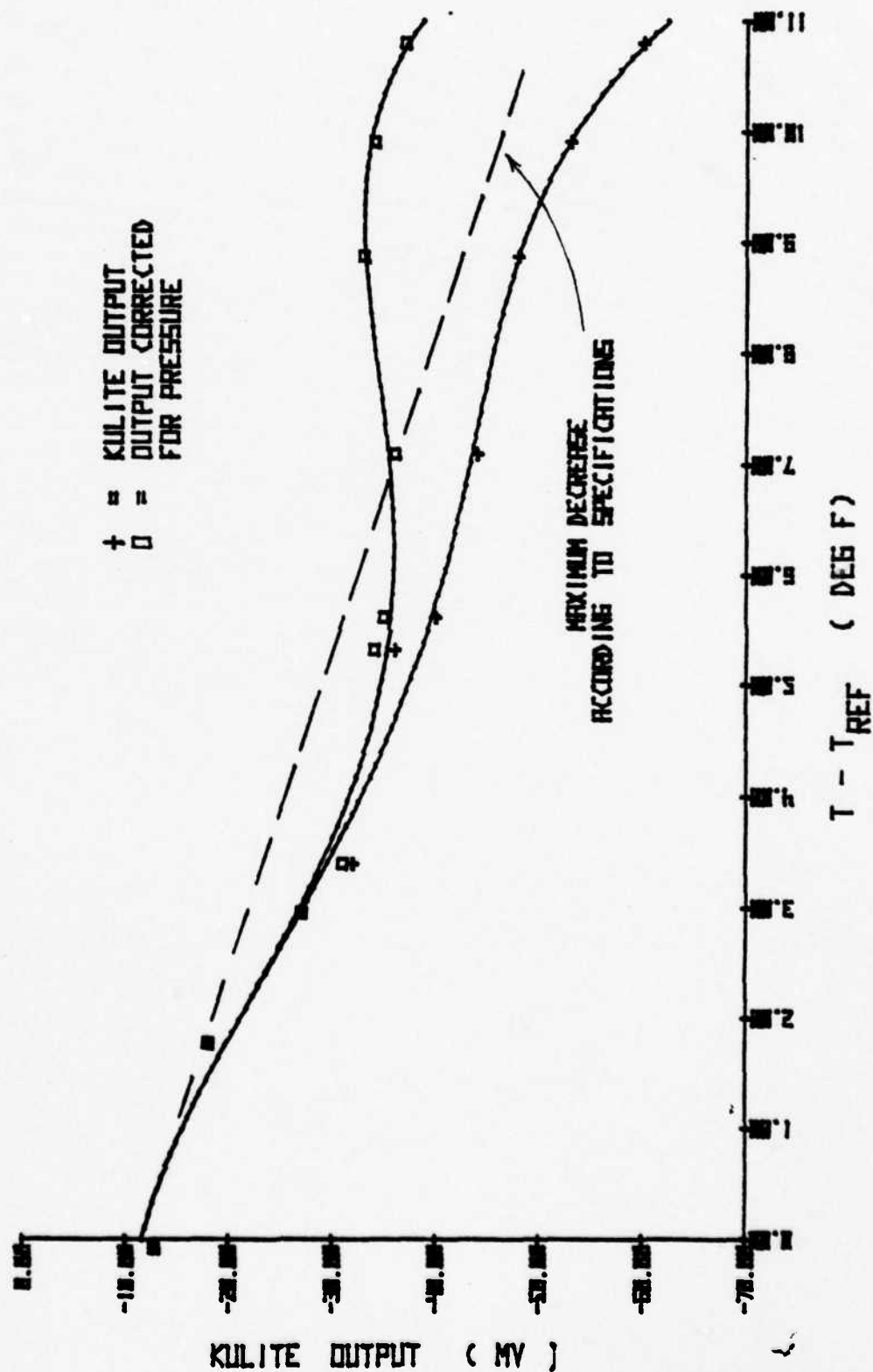
FIGURE A-1. KULITE OUTPUT CHANGE vs. TEMPERATURE

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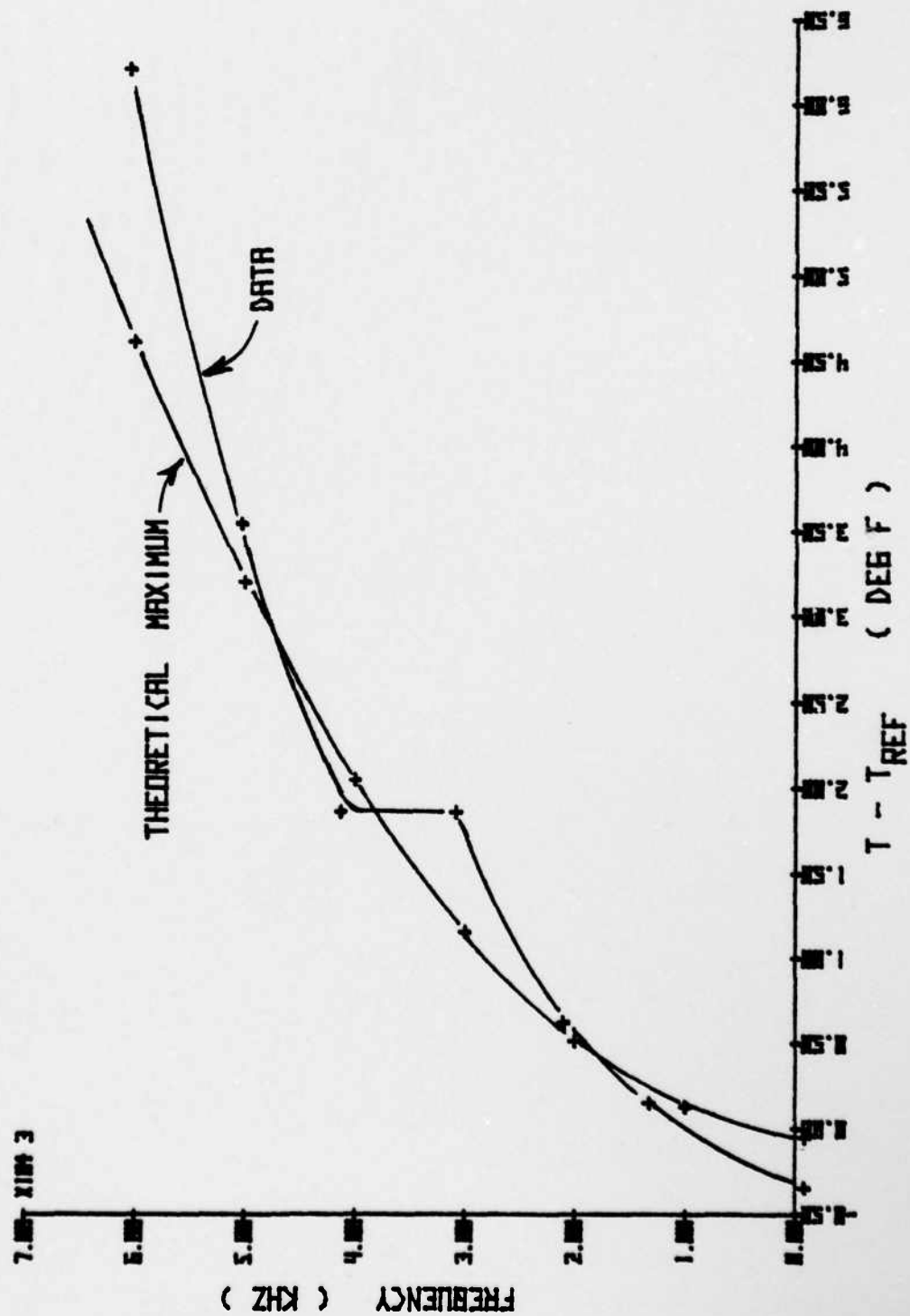
FIGURE A-2. TEMPERATURE INCREASE DUE TO WHEEL ROTATION

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APPENDIX B: COMMENTS ON KULITE PROBE CONSTRUCTION

A drawing and view of the Kulite probe are shown in Fig. 1a and Fig. 1b, respectively.

The small size of the Kulite transducer, (0.052 in O.D.) and lead wires makes them particularly susceptible to damage. The following comments are made with respect to the construction of the present probe and to any similar probe.

(1) All tubing joints must be carefully and completely deburred to prevent the insulation from being scraped off during assembly, resulting in grounding or shorting of the transducer.

(2) The tubing should be cut, formed, and fitted but not joined until the Kulite has been inserted. This reduces the number of bends that the transducer has to be pushed through.

(3) Before the transducer is inserted, it is recommended that a thin coat of lacquer or other thin protective coating be applied to any inner joints, particularly reduction collars. Since spaghetti or heat shrink tubing to protect the wires could not be obtained in sizes having sufficiently thin walls, a thin coat of brush-on insulating material was used on the last five inches of the wires.

The probe tip was assembled, ground, deburred, and then the inside was coated with lacquer. The Kulite was inserted in stages through the individual tubing sections, with a check being made at the end of each stage to insure continuity,

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absence of shorts and grounds, and satisfactory pneumatic behavior. The assembly steps are shown in Fig. B-1. A V.O.M., power supply, and pressure reference source were required for the response check. A full calibration was considered unnecessary until the probe was completed.

After inserting, bending, and positioning the Kulite in the probe tip, the open section behind the tip was filled with epoxy. It was initially intended that a metal cap be used in place of the epoxy, however it was found that the cap added little extra protection and caused transducer alignment difficulties.

Final assembly was completed with epoxy, insuring that the proper alignment was maintained. It would be desirable to mount the transducer in a semi-flexible compound such as R.T.V. to reduce vibrational shocks, however the tubing size was found to be too small.

The Kulite probe was constructed in such a way that when the ¼-inch diameter main shaft was rotated, the 1/8-inch probe shaft caused the plug through which it was inserted to rotate about the same center line. The probe tip and upper shaft were aligned so that rotation occured about the probe tip. Probe tip length was governed by the radius of the compressor plug.
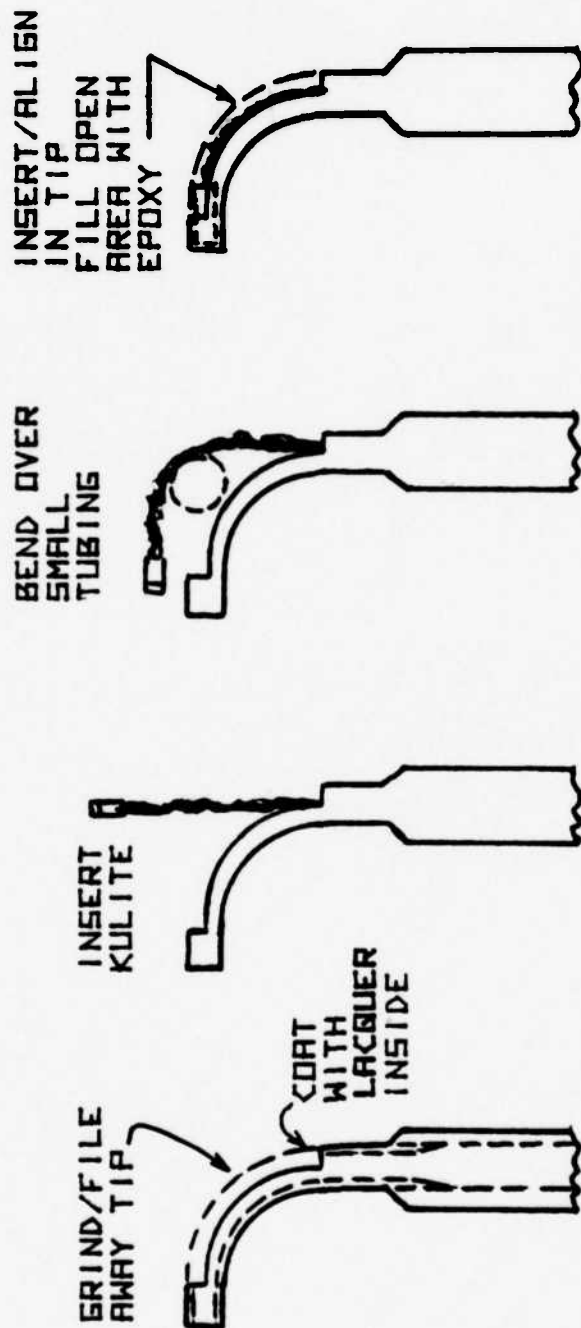
KULITE PROBE ASSEMBLY

FIGURE B-1. KULITE PROBE TIP ASSEMBLY DETAILS

APPENDIX C: APPARATUS MODIFICATIONS

C.1   THERMOCOUPLE SENSOR

A change was made in the geometry of the thermocouple
sensor in an attempt to improve the recovery factor of the
Dodge combination probe. The intent of the modification was
to reduce the sensitivity of the probe to pitch angle and
Mach number. The new tip design is shown in Fig. C-1.

A calibration of the modified probe was carried out in
a four inch diameter free jet with a similar thermocouple
reference probe located upstream in the ten inch diameter
supply pipe. It was found that the difference in temper-
ature between the two probes gave an EMF which varied line-
arly with the jet Mach number. The upstream probe indicated
a higher reading than the combination probe (total temperature
decrease through the free jet nozzle).

With the probes reversed between their respective pos-
itions, the reference probe indicated an increase in total
temperature. The data points were widely scattered, and no
Mach number dependence was decernible, however, the average
increase corresponded to 1.0 $\pm$ 0.3 degrees.

The difference in response of the two probes was prob-
ably due to a wider notch in the insulator of the reference
probe, which allowed more wire to be exposed to the airflow
near the sensor thermocouple junction. A similar insulator
could not be accommodated in the combination probe due to
the shortness of the support tubing.

It is recommended that a calibration of the two probes be carried out with respect to a common upstream reference probe.

C.2 PACER SELF TEST

Differences were observed between the averages of data taken in the free-run and in the synchronized "pacer" mode. In order to allow sampling of a calibration signal from a signal generator in the "pacer" as well as the "free-run" mode, a special circuit was designed. The circuit is shown in Fig. C-2.

Referring to Fig. C-2, the "sync." output from the signal generator was used as an input to a circuit containing a counter and an inverter. The inverted and voltage-shifted sync pulse was selected to provide the "one-per-blade" signal for the pacer. The counter was used to divide the incoming pulse frequency by 16. After inversion this provided the "one-per-rev" signal which was then synchronized with the "one-per-blade" pulse.

Labels on figure:
- PROBE SUPPORT TUBING
- INSULATER
- THERMOCOUPLE JUNCTION
- END COVERED WITH BRUSH ON INSULATING MATERIAL
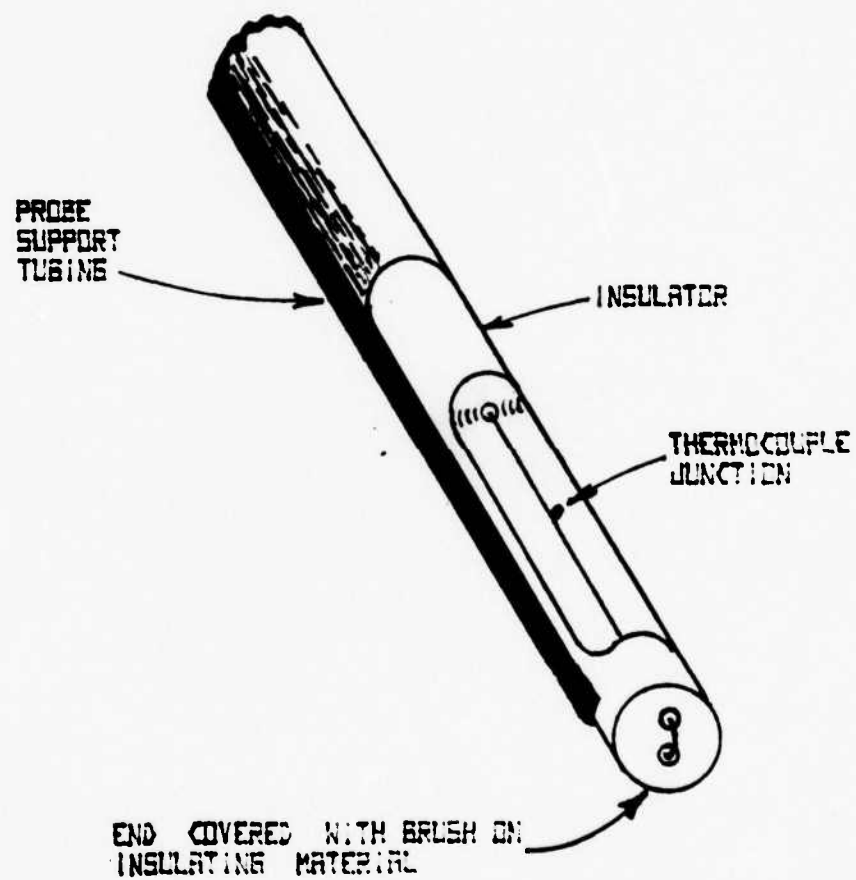
FIGURE C-1.   THERMOCOUPLE SENSOR MODIFICATION

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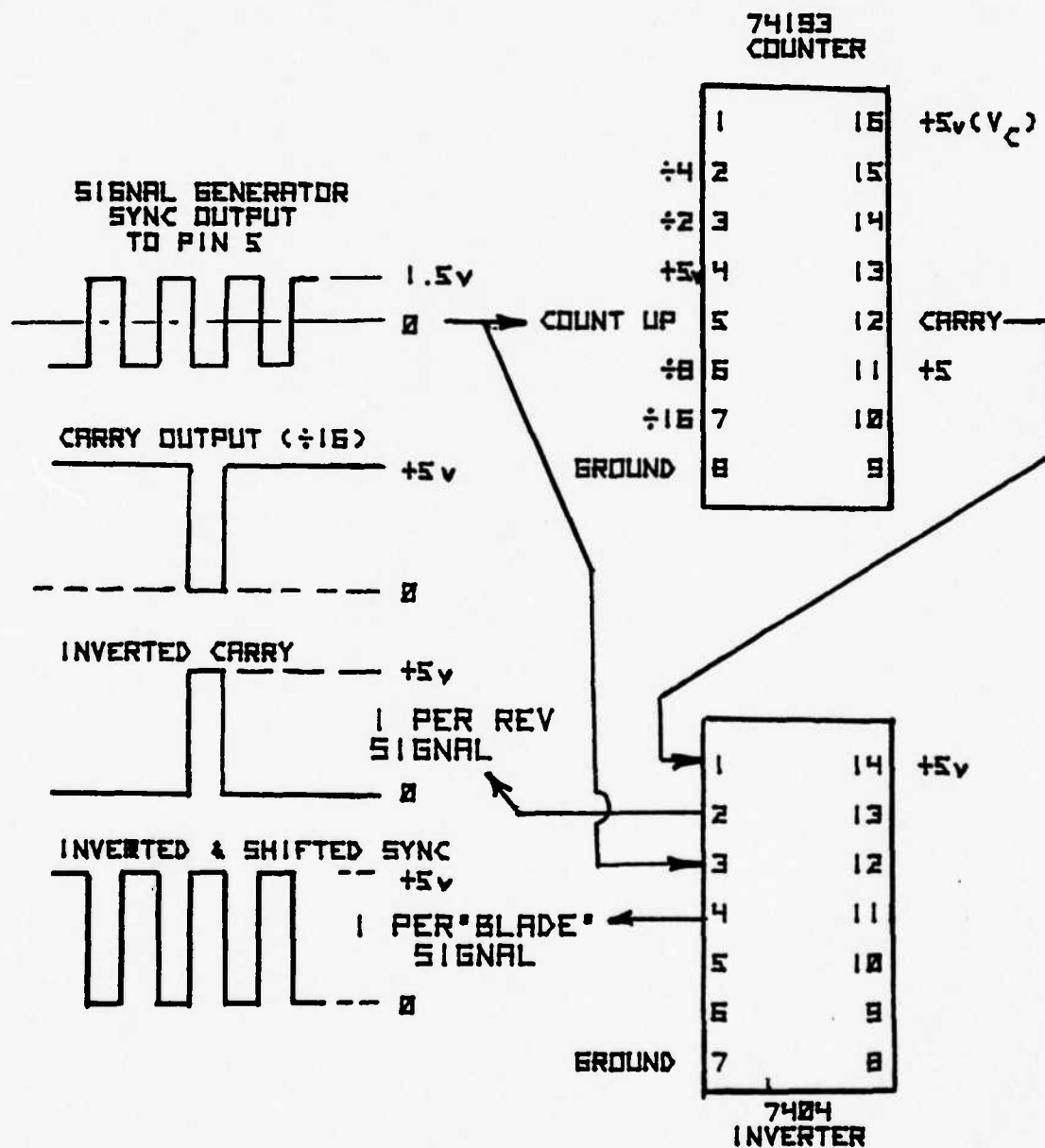
PACER TEST CIRCUIT

FIGURE C-2. REFERENCE SIGNAL GENERATION CIRCUIT

APPENDIX D: COMPUTER PROGRAMS

Two computer programs were written and used to acquire, process, plot and store data from Kulite probe measurements. The first, listed in Table D-1, was written for and used on the 21 MX computer. The function of the program was to:

(1) calibrate the incoming signal;

(2) acquire data in either the free-run or pacer mode as described in Section II and Ref. 2;

(3) compute the time average of the signal; and

(4) transfer the data samples, and other information to the HP 9830A calculator.

The transfer process was written as an option. A list of the variables used in both programs is given in Table D-2.

The second program, "Vern 2" is listed in Table D-3. It was written as a "key program" on the HP 9830A calculator. The program accepts data from the 21 MX computer and plots the data on an X-Y plotter. The program also stores data on, or recovers data from the magnetic disc mass memory storage device.

The programs depend on each other only if data transfer is required from the 21 MX to the 9830 calculator.

TABLE D-1: 21MX COMPUTER PROGRAM

```
5    REM        LAST UPDATE SEP 1977
7    REM        IF DATA TRANSFER TO 9830 DESIRED TO PLOT WAVEFORMS
10   REM        AND STORE DATA, RUN "VERN2" ON 9830 FIRST.
20   REM        A/D DATA AQUASITION, CALIBRATION AND AVERAGING PROGRAM
21   REM        IF FREE RUN MODE DESIRED WITHOUT RESTACKING OF SAMPLES
22   REM        USE F=60 AND 1681 SAMPLES WILL BE TAKEN.  IF RESTACKING
23   REM        IS DESIRED AND FREQ>1000 THEN 100 SAMPLES WILL BE TAKEN
24   REM        UP TO 255 SAMPLE POINTS MAY BE SELECTED IN ALL OTHER
25   REM        MODES OF OPERATION.  THE PROGRAM IS NOT USEFUL FOR F<500
26   REM        BECAUSE INSUFFICIENT SAMPLES WILL BE TAKEN TO COMPLETE
27   REM        ONE WAVEFORM.  THE PACER WILL NOT COUNT PROPERLY BELOW
28   REM        ABOUT 2150 CPS SINCE THEM COUNTERS OVERFLOW.
29   REM        A/D CHANNEL 3 IS ALWAYS SELECTED FOR WAVEFORM INPUT.
30   REM        THE COMPRESSOR HAS 18 BLADES.  THE SELF TEST UNIT 16.
45   DIM S(2,255),B(16),C(41,41),T(71,D(60)
53   PRINT " INPUT # OF BLADES PER REV"
54   INPUT N1
55   GOSUB 700
56   PRINT "INPUT MODE , 4= FREE , 0=PACER , ENSURE SWITCHES SET"
57   INPUT M
58   IF M=0 THEN 1400
60   PRINT "INPUT RUN #, FREQ, PTOT";
70   INPUT P,F,P2
75   IF F<100 THEN 1000
80   IF F >= 1000 THEN 120
90   PRINT "INPUT # OF SAMPLES <250";
100     INPUT S
110     GOTO 130
120  LET S=100
130  R5610(7,S(1,1),S,3,4,B(1))
140  PRINT "DATA TAKEN,  B(1) =";B(1)
160  FOR I=1 TO S
165  LET S(1,1)=(S(1,1)-2)/T4
180  NEXT I
200  PRINT# 6
```

```
210 PRINT# 6;"RUN #";R," PTOT =";P2,"FREQ =";F
220 PRINT# 6
221 REM    ASSIGN TIME VALUES
230 LET S(2,1)=0
240 FOR I=1 TO S-1
250 LET S(2,I+1)=.00001*I
260 IF S(2,I+1) <= 1/F THEN 310
270 FOR J=1 TO S-1
280 LET S(2,I+1)=S(2,I+1)-1/F
290 IF S(2,I+1) <= 1/F THEN 310
300 NEXT J
310 NEXT I
315 REM RE-ARRANGE DATA
320 LET C=0
330 FOR I=2 TO S-1
340 IF S(2,I) <= S(2,I+1) THEN 420
350 LET C=1
360 LET T=S(2,I+1)
370 LET S(2,I+1)=S(2,I)
380 LET S(2,I)=T
390 LET U=S(1,I+1)
400 LET S(1,I+1)=S(1,I)
410 LET S(1,I)=U
420 NEXT I
430 IF C=1 THEN 320
432 PRINT "IF DATA XFER NOT DESIRED ENTER 1"
434 INPUT C
436 IF C=1 THEN 535
440 PRINT# 8;S
450 PRINT# 8;F
460 PRINT# 8;R
470 PRINT# 8;B(I)
475 PRINT# 8;M
476 PRINT# 8;P2
480 FOR I=1 TO S
490 PRINT# 8;S(1,I)
500 NEXT I
```

```
510  FOR I=1 TO S
520  PRINT# 8;S[2,I]
530  NEXT I
535  IF M=0 THEN 600
540  LET A=0
550  FOR I=1 TO S-1
560  LET A=A+(S[1,I]+S[1,I+1])*(S[2,I+1]-S[2,I])/2
570  NEXT I
575  LET A=A+((S[1,S]+S[1,1])/2)*(1/F-S[2,S])
580  LET B=A*F
590  PRINT# 6;"  MODE =";M,"   THE TIME AVERAGE IS :";B
600  PRINT# 6
605  IF C=1 THEN 615
610  PRINT# 8;B
615  PRINT "IF FURTHER RUNS DESIRED AT THIS CALIBRATION ENTER 1";
620  INPUT C
630  IF C=1 THEN 56
640  END
700  REM       CALIBRATION ROUTINE
701  PRINT "IF LEAST SQUARES FIT DESIRED, READY SR-51 AND ENTER 1"
710  INPUT D
720  IF D#1 THEN 802
730  PRINT "ENSURE PACER OFF & INPUT # OF CAL POINTS"
740  INPUT C
750  LET Z=0
760  GOTO 824
800  REM ADJUST ZERO BALANCE FIRST
802  PRINT " SET PREF =0 , ENSURE PACER OFF, AND INPUT # OF CAL POINTS"
805  INPUT C
806  REM       COMPUTE ZERO INTERCEPT
807  RS610(7,C[1,1],1681,3,4,B[1])
809  PRINT "DATA TAKEN"
811  LET T=0
812  FOR I=1 TO 41
814  FOR J=1 TO 41
816  LET T=T+C[I,J]
818  NEXT J
820  NEXT I
```

```
822  LET Z=T/1681
824  FOR I=1 TO 7
825  LET T(I)=0
826  NEXT I
827  PRINT# 6;" CALIBRATION RESULTS : # OF POINTS =";C
830  FOR I=1 TO C
840  PRINT "ENTER P REF (GAGE)";
850  INPUT Y
856  R5610(7,C(1,I),1681,3,4,B(I))
857  PRINT "DATA TAKEN"
858  LET T=0
860  FOR K=1 TO 41
861  FOR J=1 TO 41
862  IF ABS(C(K,J))<.998 THEN 864
863  PRINT " SAMPLES OVER-RANGING"
864  LET T=T+C(K,J)
866  NEXT J
868  NEXT K
869  REM   COMPUTE SLOPE
870  LET T(I)=(T/1681-Z)/V
875  PRINT " PPEF = ";Y," VOLTS =";T/1681
876  PRINT# 6;" PREF(X-COORD) = ";Y," VOLTS(Y-COORD) = ";T/1681
880  NEXT I
882  LET T=0
883  FOR I=1 TO C
884  LET T=T+T(I)
885  NEXT I
886  LET T4=T/C
895  PRINT# 6
900  IF D#1 THEN 910
902  PRINT "INPUT ZERO INTERCEPT AND SLOPE (DV/DP)"
904  INPUT Z,T4
906  GOTO 920
910  PRINT# 6;"THE SLOPES ARE,;";T(1);T(2);T(3)
915  PRINT# 6;T(4),T(5),T(6),T(7)
920  PRINT# 6;"P= ZERO INTERCEPT=";Z;" AVERAGE SLOPE (DV/DP) =";T4
930  PRINT# 6
940  PRINT# 6
```

```
950    PRINT# 6
960    RETURN
980    REM    FREE RUN ROUTINE USING 1681 SAMPLES COVERING 1/60 SEC
1000   LET S=1681
1010   R5610(7,C[1,1],1681,3,4,B[1])
1015   PRINT "DATA TAKEN"
1020   LET T=0
1030   FOR I=1 TO 41
1040   FOR J=1 TO 41
1041   IF ABS(C[I,J])<.998 THEN 1045
1042   PRINT " SAMPLES OVER-RANGING"
1045   LET C[I,J]=(C[I,J]-2)/T4
1050   LET T=T+C[I,J]
1060   NEXT J
1070   NEXT I
1080   LET B=T/1681
1081   PRINT# 6
1082   PRINT# 6;" RUN # ";R," PTOT = ";P2," FREQ =";F
1083   PRINT# 6
1084   PRINT# 6;"THE TIME AVERAGE IS :";B
1085   PRINT# 6
1086   PRINT "IF DATA TRANSFER NOT DESIRED ENTER 1"
1087   INPUT C
1088   IF C=1 THEN 615
1089   REM        TRANSFER DATA TO 9830
1090   PRINT# 8;S
1100   PRINT# 8;F
1110   PRINT# 8;R
1120   PRINT# 8;B[1]
1130   PRINT# 8;M
1140   PRINT# 8;P2
1150   FOR I=1 TO 41
1160   FOR J=1 TO 41
1170   PRINT# 8;C[I,J]
1180   NEXT J
1190   NEXT I
```

```
1200  PRINT# 8;B
1210  GOTO 615
1400  REM PACER ROUTINE
1401  PRINT "IF SAMPLING AT SAME POINT IN EVERY PAIR ENTER 1"
1402  INPUT C
1403  IF C=1 THEN 1720
1410  PRINT "INPUT BLADE PAIR , START PT , & # OF SAMPLES PER PT < 60"
1420  INPUT P,K,S1
1430  PRINT "INPUT # OF SAMPLES POINTS,     RUN # ,     PTOT"
1440  INPUT S,R,P2
1450  LET P1=32768+256*P+K
1460  LET A=Q=0
1470  FOR I=0 TO S-1
1480  LET X=0
1490  PPACF(P1,J,A5)
1500  PS610(7,D(1),S1,3,0,B(1))
1510  FOR J=1 TO S1
1520  LET X=X+D(J)
1530  NEXT J
1540  LET X=Y/S1
1542  IF APS(Y)<.998 THEN 1550
1543  PRINT "SAMPLES OVER-RANGING"
1550  LET S(1,I+1)=(X-2)/T4
1560  LET A=A+S(1,I+1)
1570  PRINT I,N,X
1580  LET Q=Q+N
1590  LET P1=P1+1
1600  NEXT I
1610  LET Q=S*N1*250000/Q
```

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```
1615  PRINT# 6
1620  PRINT# 6;"RUN # ";R;"  PTOT =";P2;"  FREQ=";Q
1623  PRINT# 6;" BLADE PAIR = ";P,"  # OF SAMPLES PER PT =";S1
1635  LET F=Q
1638  REM     ASSIGN TIME VALUES
1640  FOR I=1 TO S
1670  LET S(2,I)=(I-1)*2/255/F
1680  NEXT I
1690  LET B=A/S
1702  PRINT# 6;" THE TIME AVERAGE IS:";R
1710  GOTO 432
1720  PRINT " INPUT SAMPLES PER POINT  &  TOTAL # OF SAMPLE POINTS"
1730  INPUT S1,S
1740  PRINT "INPUT RUN # , PTOT "
1750  INPUT P,P2
1760  PRINT "INPUT START POINT"
1765  INPUT P1
1770  LET P=99
1780  GOTO 1460
```

TABLE D-2: <u>LIST OF VARIABLES</u>

<u>VARIABLE</u>	<u>USE</u>
S(2,255)	An array in which the first row stores reduced data samples. The second row stores the time assigned to samples based on frequency(first sample assigned time = 0).
C(41,41)	An array of 1681 data samples are taken in the free-run mode, and stored row-wise. It is used in the calibration procedure or at any time the frequency is input as < 100. (At 10 microsecond intervals, the elapsed time is 1/60 sec, ie. F = 60)
B(16)	A return variable indicating which A/D channel was actually sampled.
T(7)	An array storing the slopes of each calibration point when a least squares routine is not used.
D(60)	An array storing raw data samples before averaging and reduction to the calibrated quantity.
A	An accumulator storing the "area" of the sampled waveform.
A5	RPACE return variable (not used)
B	The average value of the waveform.
C	The number of calibration points and/or a general decision variable. *
D	A decision variable.*
F	The frequency of the sampled waveform.**
M	A/D Mode (4 = Free-run, 0 = Pacer)*
N	The number of computer clock cycles between "one per rev" pulses.
N1	The number of "blades per rev".*

TABLE D-2: (CONTINUED) <u>LIST OF VARIABLES</u>

P
The selected blade pair (set to 99 if samples are taken in every passage)**

P1
The sample location on the wheel in the 21 MX program (there are 128 X N1 locations)** It is the atmospheric pressure in the 9830 program.

P2
The total pressure (used only as a reference for scaling in the plotting program)*

Q
Frequency accumulator/frequency

R
Run number (used only for storing data on mass memory files or recovering data from files)*

S
The number of sample points/locations.*

S1
The number of samples to be taken at each of the "S" sample points.*

T
A temporary accumulator.

T4
The slope of the final calibration curve.**

U
A temporary storage location.

X
A temporary accumulator.

Z
The zero intercept of the calibration curve.**

*
Required input variable.

**
Optional input variable. It may be an output variable depending on data acquisition mode or method of calibration.

```
5 REM **  "VERN2"  FOR USE WITH KULITE DATA ACQUISITION **
20 REM ENTER PATMOS(P1) (IN HG) IN LINE 35
30 REM KEY1=PLOT PROGRAM;KEY6 = STORAGE OF POINTS 1 TO 20
35 REM  KEY 16 = RETREVIAL OF POINTS 1-20 FROM DISK
40 REM  KEY 3 & 13 ARE STORAGE AND RETREVIAL OF MISC RUNS
50 DIM S[2,255],B[1],C[41,41]
55 REM ENTER PATMOS IN NEXT LINE
60 P1=29.85
70 MAT S=ZER
80 MAT C=ZER
90 ENTER (1,*)S
100 ENTER (1,*)F
110 ENTER (1,*)R
120 ENTER (1,*)B[1]
130 ENTER (1,*)M
140 ENTER (1,*)P2
150 IF F<100 THEN 310
160 FOR I=1 TO S
170 ENTER (1,*)S[1,I]
180 NEXT I
190 FOR I=1 TO S
200 ENTER (1,*)S[2,I]
210 NEXT I
220 ENTER (1,*)B
230 IF B[1]=3 THEN 260
240 DISP "ERROR CHANNEL=";B[1]
250 WAIT 32000
260 PRINT LIN4
270 PRINT " RUN #:";R;"      PTOT =";P2;"FREQ =";F
280 PRINT
290 PRINT " MODE =";M;"   THE TIME AVERAGE IS :";B
300 END
310 FOR I=1 TO 41
320 FOR J=1 TO 41
330 ENTER (1,*)C[I,J]
340 NEXT J
350 NEXT I
360 GOTO 220
```

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TABLE D-3 (CONT'D)

```
5 REM KEY1 ; PLOT PROGRAM ; RUN KEY 0 FIRST TO INITIALIZE
6 REM THEN STOP MAIN PROGRAM AND CONT KEY 1
10 C=F
20 IF M=4 OR S <= 127 THEN 40
30 F=F/2
40 SCALE -0.2/F,1.15/F,-0.8*P2,1.4*P2
50 XAXIS -0.6*P2,0.1/F,0,1/F
60 XAXIS 1.2*P2,0.1/F,0,1/F
70 YAXIS 0,0.1*P2,-0.6*P2,1.2*P2
80 YAXIS 1/F,0.1*P2,-0.6*P2,1.2*P2
90 IF F<100 THEN 380
100 PLOT 0,S[1,1],-2
110 FOR I=2 TO S
120 PLOT S[2,I],S[1,I]
130 NEXT I
140 PEN
150 FORMAT F6.3
160 FORMAT F5.1
170 LABEL (*,1.4,1.7,0,8/11)
180 FOR I=1 TO 10
190 PLOT I*0.1/F,-0.6*P2
200 CPLOT -4,-1.2
210 LABEL (150)I*100/F
220 NEXT I
230 FOR I=-0.6 TO 1.2 STEP 0.2
240 PLOT 0,I*P2
250 CPLOT -5.5,-0.3
260 LABEL (160)I*P2
270 NEXT I
280 LABEL (*,2.1,1.7,0,8/11)
290 PLOT -0.05/F,1.25*P2,1
300 D=0.1*INT(10*B)
310 LABEL (*)" TRANSX  POINT #";R;" FREQ =";C;"  AVE = ";D
320 PLOT 0.37/F,-0.77*P2,1
330 LABEL (*)"TIME  (MSEC)"
340 PLOT -0.11/F,0.65*P2,1
350 LABEL (*,2,1.7,3*PI/2,8/11)"P-PR  (IN H2O)"
360 DISP "PLOT COMPLETE"
370 END
380 T=0
390 PLOT T,C[1,1],-2
400 FOR I=1 TO 41
410 FOR J=1 TO 41
420 PLOT T,C[I,J]
430 T=T+0.00001
440 NEXT J
450 NEXT I
460 GOTO 140
```

```
10 REM KEY 6,STORAGE FOR  PACER RUNS 1-20
20 DIM SS[2,255]
30 FILES P1,P2,P3,P4,P5,P6,P7,P8,P9,P10
40 IF R>10 THEN 130
50 PRINT #R;R,F,S,P2,P1,B,M
60 FOR I=1 TO S
70 PRINT #R;S[1,I]
80 NEXT I
90 FOR I=1 TO S
100 PRINT #R;S[2,I]
110 NEXT I
120 GOTO 210
130 FILES P11,P12,P13,P14,P15,P16,P17,P18,P19,P20
140 PRINT #R-10;R,F,S,P2,P1,B,M
150 FOR I=1 TO S
160 PRINT #R-10;S[1,I]
170 NEXT I
180 FOR I=1 TO S
190 PRINT #R-10;S[2,I]
200 NEXT I
210 END
```

```
10 REM KEY 16, PACER DATA RETREVIAL, RUNS 1-20
20 DIM SS[2,255]
30 DISP "INPUT RUN # DESIRED";
40 INPUT R
50 IF R>10 THEN 150
60 FILES P1,P2,P3,P4,P5,P6,P7,P8,P9,P10
70 READ #R;R,F,S,P2,P1,B,M
80 FOR I=1 TO S
90 READ #R;S[1,I]
100 NEXT I
110 FOR I=1 TO S
120 READ #R;S[2,I]
130 NEXT I
140 GOTO 230
150 FILES P11,P12,P13,P14,P15,P16,P17,P18,P19,P20
160 READ #R-10;R,F,S,P2,P1,B,M
170 FOR I=1 TO S
180 READ #R-10,S[1,I]
190 NEXT I
200 FOR I=1 TO S
210 READ #R-10;S[2,I]
220 NEXT I
230 END
```

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